



SSSWG MEETING #22

PRESENTATION MATERIALS

NOVEMBER 28, 1989

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TUESDAY NOVEMBER 28, 1989

LOCATION: JOHNSON SPACE CENTER
BUILDING 30 AUDITORIUM
Houston, Texas

PRESENTATIONS:

Robotic Servicing In The Nuclear Industry Applied To The Needs Of Satellite Servicing And Lunar And Mars Exploration

Proposed 10-Year National Research, Development, and Demonstration Program For Robotics To Support Remote Operations For Energy System Applications

20 Year Forecast of NASA Robotics Requirements for Space Exploration

A Generalized Modular Architecture For Robot Structures

Thirty-Year Forecast: The Concept Of A Fifth Generation Of Robotics-The Super Robot

Del Tesar/ University of Texas

Challenger Center for Space Science Education

Jane Smith and Lisa Turner/ Challenger Center

Sharing the Dream

Chuck Woolley/ NASA-JSC

Designing Equipment For Remote Handling: Lessons Learned From Nuclear Technology

Dan Kuban/ Oak Ridge National Laboratory (ORNL)

ROBOTIC SERVICING IN THE NUCLEAR INDUSTRY APPLIED TO THE NEEDS OF SATELLITE SERVICING AND LUNAR AND MARS EXPLORATION

NOVEMBER 28, 1989

DEL TESAR/ UNIVERSITY OF TEXAS

**PROPOSED 10-YEAR NATIONAL RESEARCH,
DEVELOPMENT, AND DEMONSTRATION
PROGRAM FOR ROBOTICS
TO SUPPORT REMOTE OPERATIONS
FOR ENERGY SYSTEM APPLICATIONS**

by

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512-471-3039**

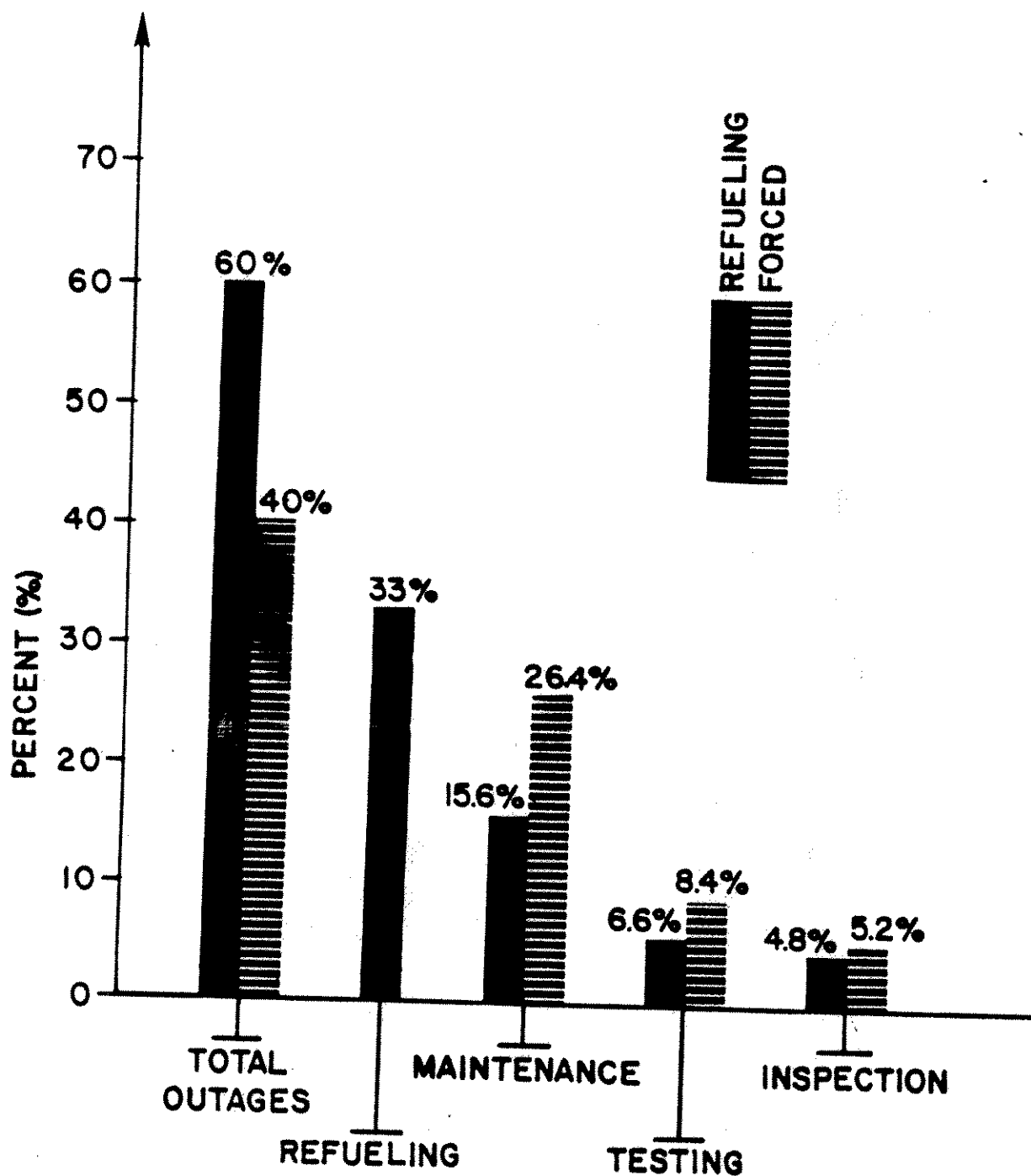
AUGUST 1986

**ANNUAL POWER REPLACEMENT AND ORE COSTS PER
PLANT FOR VARIOUS WORK CATEGORIES
IN MATURE LWR PLANTS**

WORK CATEGORY	COST (MILLION \$'S)
Maintenance	24.9
Refueling	16.0
Testing and Inspection	12.2
Waste Processing	0.68
Surveillance Operations	0.66
TOTAL	54.4

**Based On: Power Replacement Cost of \$500,000 Per Day;
Ore Costs of \$20,000 Per Man-Rem for Plants
of 600 to 700 MW(E).**

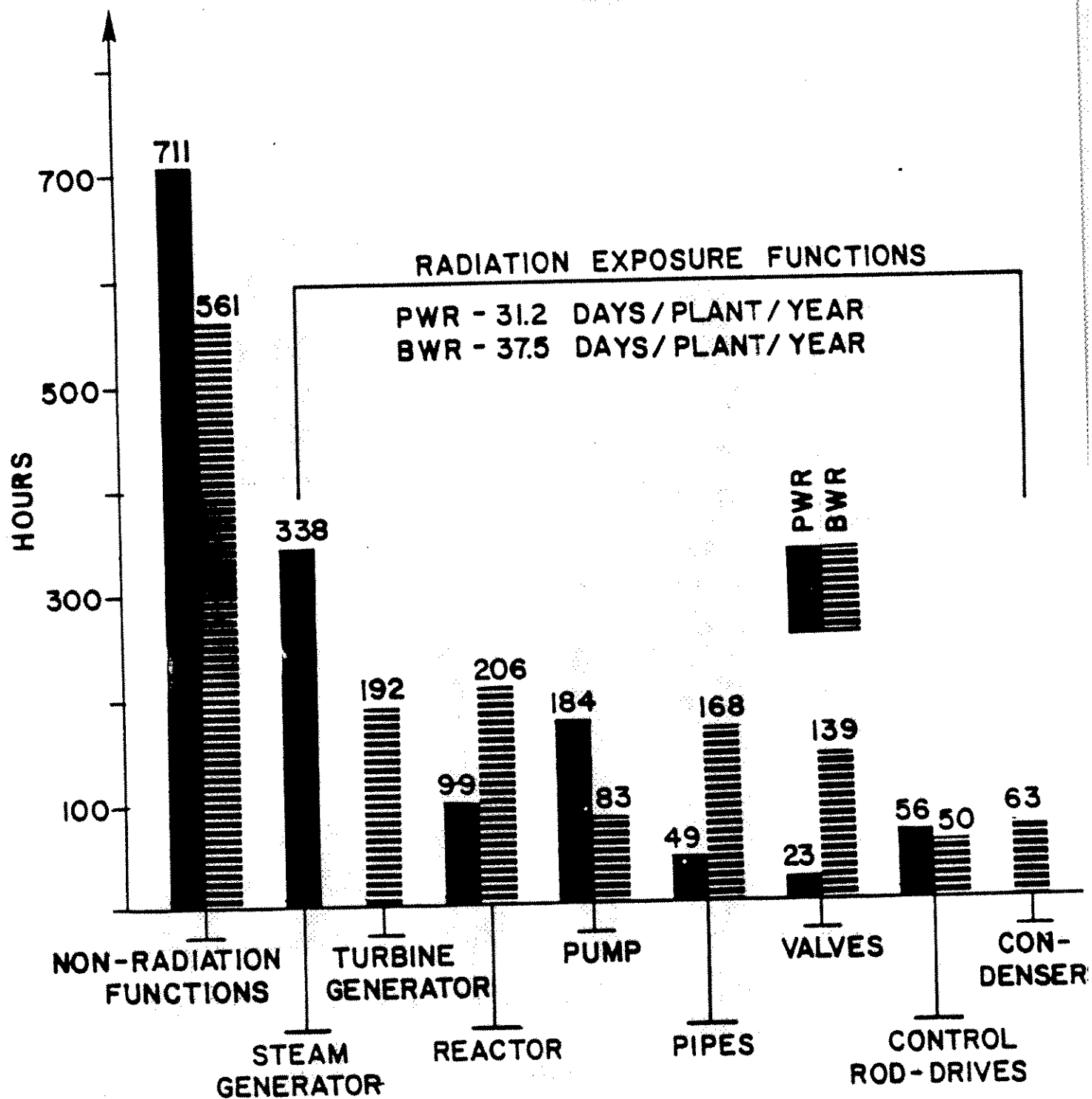
PERCENT TOTAL UNAVAILABILITY IN MATURE LWR
PLANTS DUE TO FORCED OR REFUELING OUTAGES
(90 DAYS/YEAR OR 25% UNAVAILABILITY)



SOURCE: EPRI NP-755, APRIL, 1978

FIGURE 1

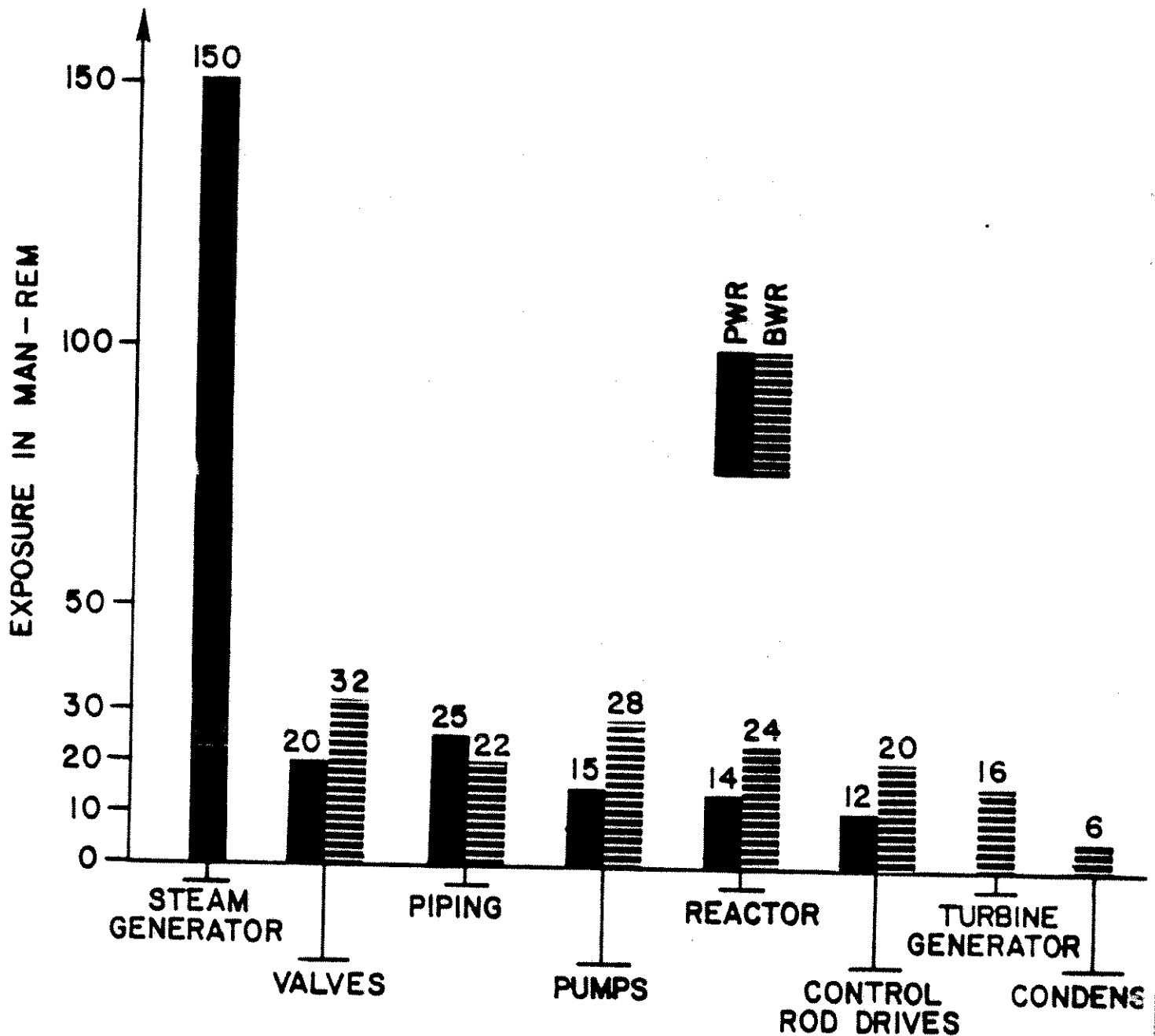
OUTAGE TIMES BY SYSTEM COMPONENT (TOTAL OUTAGE TIMES DUE TO MAINTENANCE, TESTING, AND INSPECTION)



SOURCE : EPRI NP-755, APRIL, 1978

FIGURE 3

AVERAGE ANNUAL MAN-REM EXPOSURES FOR KEY PLANT COMPONENTS (1969-1977)



REPRESENTATIVE SOURCES:

SCIENCE APPLICATION INCORPORATED
REP. AIF/NESP - 005, SEPT. 1974

J. VANCE, ET. AL. IMPACT OF 500 MREM/YEAR
ORE LIMIT, AIF REPORT, APRIL, 1978

FIGURE 5

OPERATIONAL BENEFITS OF IMPROVED REMOTE SYSTEMS TECHNOLOGY

- 1. Reduction of Man-Rem Exposure**
- 2. Reduction In Work Force Size**
- 3. Increased Quality of Repair Work**
- 4. Increased Plant Availability**
- 5. Reduced Service Tool Wear & Tear**
- 6. Reduced Cost Due to Generic Application
to Broad Range of Tasks**

NEAR TERM PROJECTED SAVINGS (1990)

1. **By 1990 140 Plants May Be On-Line**
2. **Projected Cost or Maintenance Would Be \$2.6 Billion/Year**
3. **Projected Remote Systems Savings Would Be \$1.8 Billion/Year**
4. **Maintenance Savings on PWR Steam Generator and BRW Valve Would Be \$690.000.000/Year**
5. **Annual Investment of \$50.000.000 Would Yield a Benefit-Cost Ratio of 10**

OTHER ENERGY RELATED APPLICATIONS FOR REMOTE SYSTEMS TECHNOLOGY

WHY?

Reduces Hazards to Personnel and Generates an
Economic Benefit

1. Accident Missions
2. Coal Mining Operations
3. Ocean Floor Oil and Mineral Operations
4. Remote Operations in Space
5. Arctic Exploration and Field Operations
6. Energy Test Facilities (Fusion)
7. Nuclear Fuel Reprocessing
8. Maintenance of High Voltage Transmission Lines
9. Decommissioning of Nuclear Facilities
10. Operations Following Major Unplanned Events Such as TMI

DEVELOPMENT COST FOR
SHUTTLE MANIPULATOR
(1975 - 1980)

<u>DEVELOPMENT PHASE</u>	<u>COST</u>
1. Initial Design	\$ 5,000,000
2. Engineering Design & Component Evaluation	\$ 35,000,000
3. Qualification of Flight Ready Hardware	\$ 35,000,000
4. Build & Test Delivered Hardware	\$ 25,000,000
	<hr/>
TOTAL COST	\$100,000,000

**TABLE 5.2 LEVEL OF ROBOTIC R&D EFFORT
RECOMMENDED FOR EACH SERVICE TASK**

SERVICE TASK	WEIGHTING FACTOR	RECOMMENDED LEVEL R&D EFFORT
1. Steam Generator Maintenance	1.0	████████████████████ 69
2. Valve and Pipe Replacement	0.8	████████████████ 49
3. Component Replacement	0.7	██████████████ 40
4. Refueling Service	0.5	██████████ 23
5. In-Service Inspection	0.3	██████ 10
6. Filter Changing	0.3	██████ 9
7. Surveillance	0.2	████ 7
8. Underwater Operations	0.2	██████ 11
9. Waste Handling	0.2	██ 5
10. General Plant Decontamination	0.2	██████ 9

PROPOSED DEVELOPMENT AND IMPLEMENTATION PROGRAM

I. DEVELOPMENT PROGRAM

1. <u>Basic Research</u> in Robotics in Universities at \$5,000,000/Year	\$ 50,000,000
2. <u>Component Developments</u> in Robotics Jointly by Universities and Industry at \$5,000,000/Year	\$ 50,000,000
3. <u>System Demonstrations</u> in Robotics Jointly by Universities and Industry at \$10,000,000	\$100,000,000
	<hr/>
SUBTOTAL	\$200,000,000

II. DEVELOPMENT PROGRAM

4. <u>Construction & Development</u> of 50 Remote Systems at \$5,000,000 Each	\$250,000,000
5. <u>Operating Costs</u> of \$500,000/Year For 100 Operating Years	\$ 50,000,000
	<hr/>
SUBTOTAL	\$300,000,000

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TOTAL COST OF PROGRAM	\$500,000,000
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**RANKING OF ECONOMIC SIGNIFICANCE
OF
VARIOUS ENERGY SYSTEM APPLICATIONS**

	Near Term (0 to 20 years)	Long Term (20 to 40 years)
<hr/>		
1. FISSION REACTORS	10	10
2. OIL PRODUCTION IN OCEAN	5	5
3. COAL PRODUCTION	3	3
4. FUEL HANDLING AND PROCESSING	2	2
5. FUSION REACTORS	1	8

CHART I. NEAR AND LONG-TERM RANKING OF VARIOUS ENERGY SYSTEM APPLICATIONS

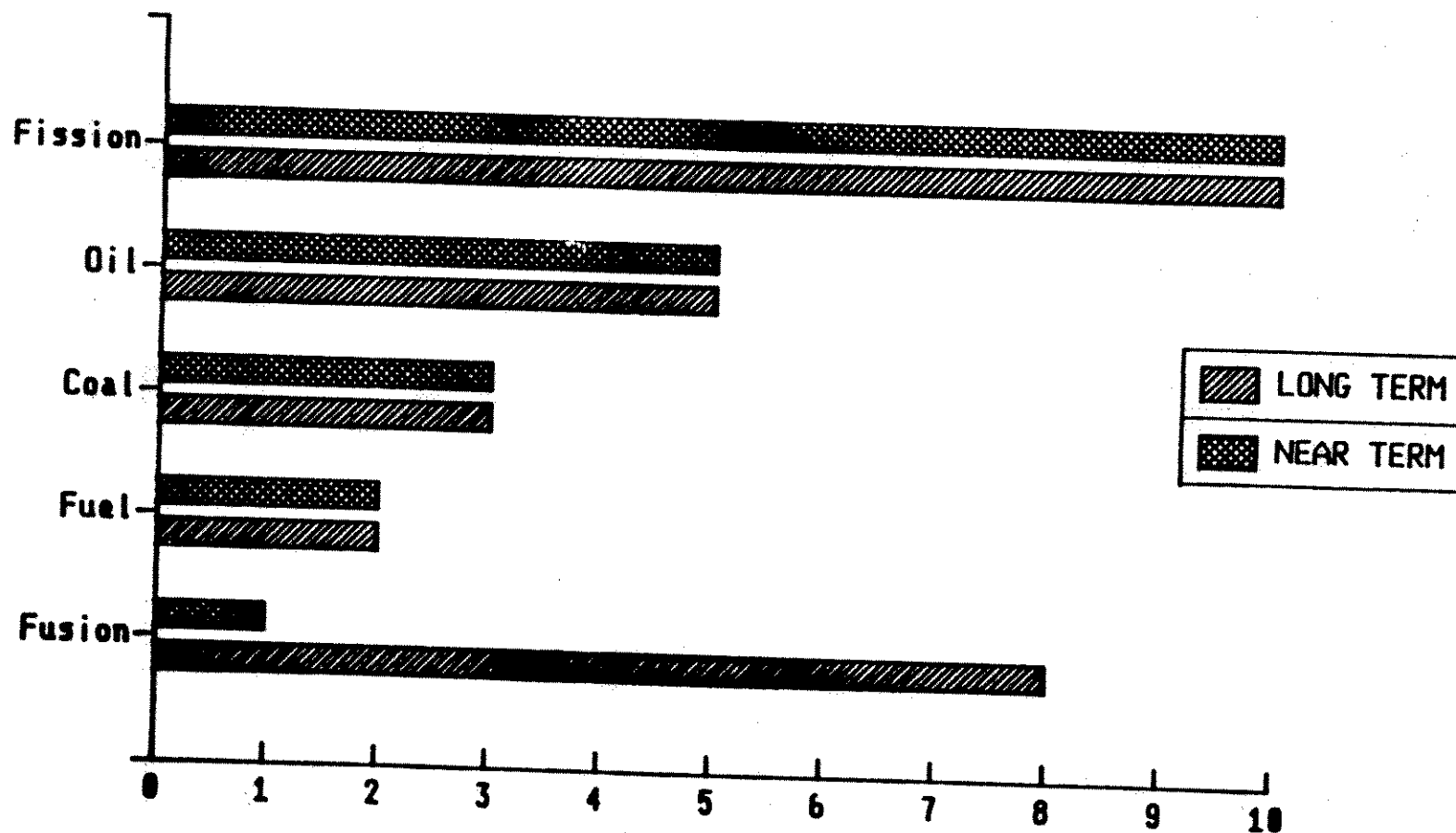


Table II

**NEAR AND LONG TERM RANKING OF
COMPONENT TECHNOLOGIES FOR
ENERGY SYSTEM ROBOTICS APPLICATIONS**

	Near Term Availability (Normalized)	Near Term Ranking (Normalized)	Long Term Ranking (Normalized)
1. Man-Machine Interface	0.25	7.4	10.0
2. Geometry	0.50	10.0	6.8
3. Actuator Modules	0.20	4.0	6.8
4. Prime Movers	0.35	6.4	6.2
5. Intelligent Control	0.15	2.7	6.1
6. End-Effectors	0.15	2.7	6.1
7. Artificial Intelligence	0.10	1.7	6.0
8. Vision	0.10	1.7	5.7
9. Graphics/CAD	0.35	5.9	5.7
10. Sensors	0.30	4.9	5.6
11. Communication Interfaces	0.15	2.4	5.5
12. Computer Architecture	0.20	2.7	4.9
13. Software Modules	0.05	0.7	4.8
14. Dynamics	0.15	1.9	4.4

CHART II. LONG-TERM RANKING OF COMPONENT TECHNOLOGIES

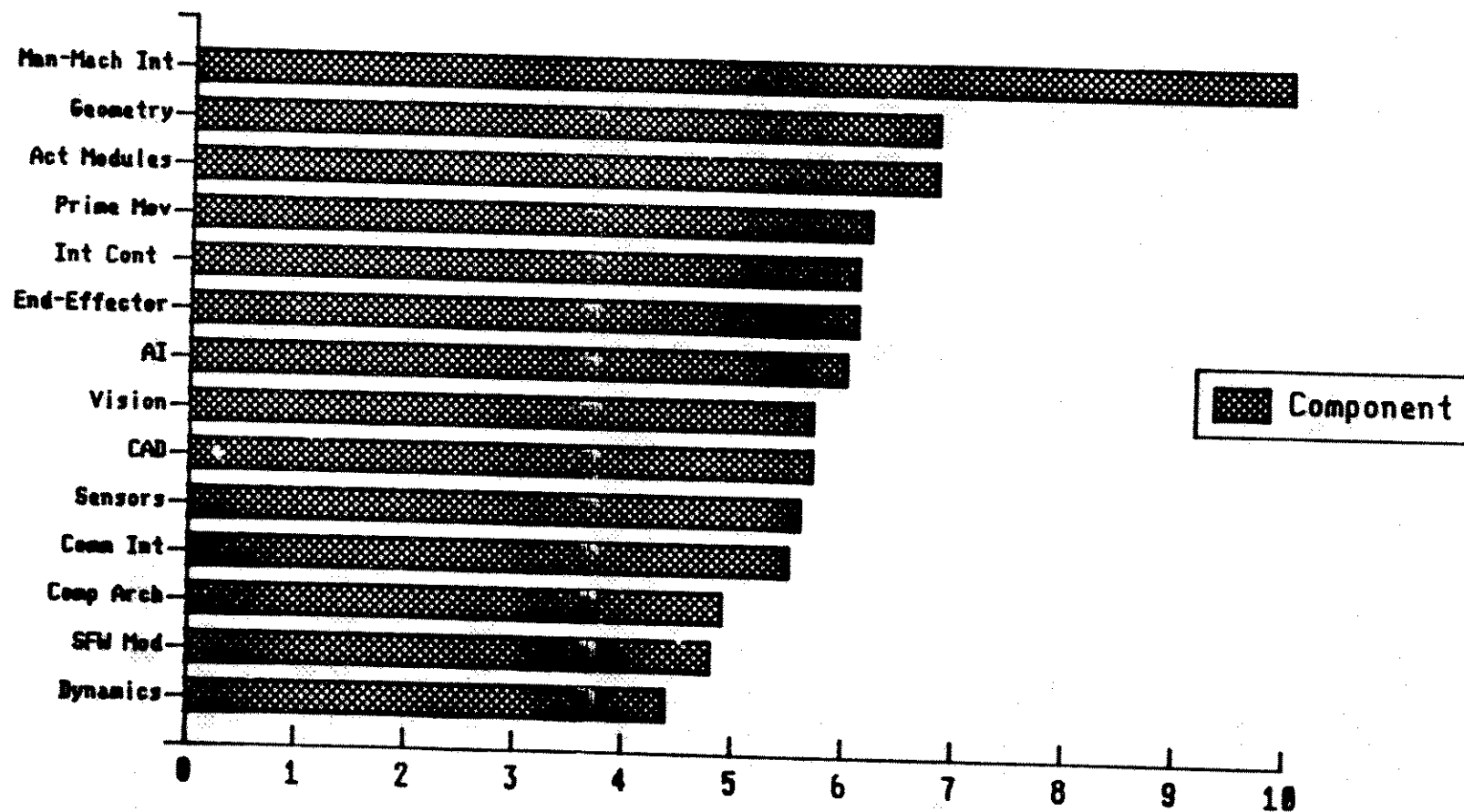
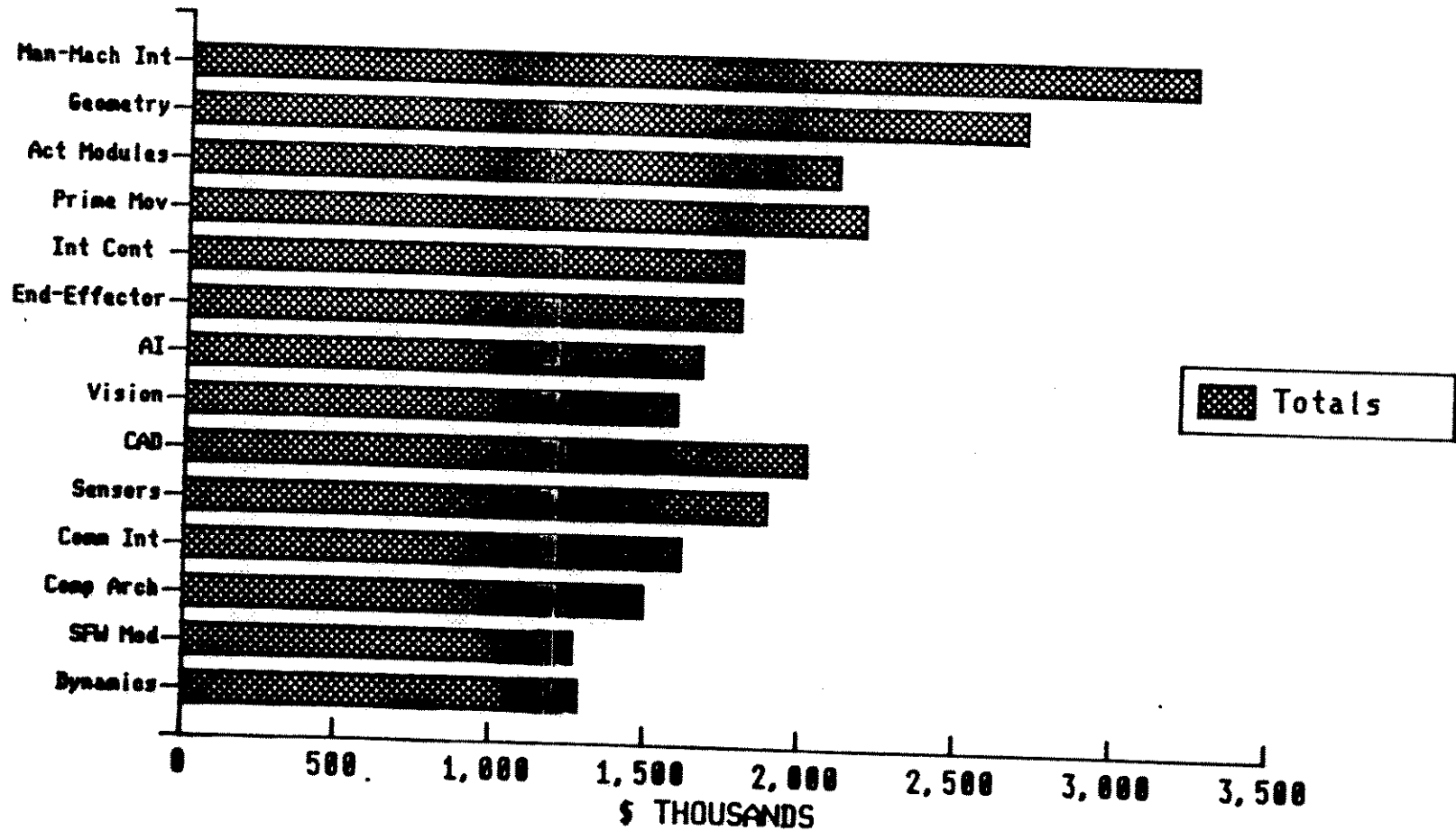


TABLE IIA

**RECOMMENDED YEARLY FUNDING FOR
COMPONENT TECHNOLOGY DEVELOPMENT
IN THE NEAR AND MIDDLE TERM (\$K)**

	Level I	Level II	
	R&D	Adv. Development	
	Near Term	Middle Term	Long Term
1. Man-Machine Interface	247	500	250
2. Geometry	333	340	170
3. Actuator Modules	133	340	170
4. Prime Movers	213	310	155
5. Intelligent Control	90	305	152
6. End-Effectors	90	305	152
7. Artificial Intelligence	57	300	150
8. Vision	57	285	142
9. Graphics/CAD	197	385	142
10. Sensors	163	280	140
11. Communication Interfaces	80	275	137
12. Computer Architecture	90	245	122
13. Software Modules	23	240	120
14. Dynamics	63	220	110
Yearly Average Total	1836	4014	2007

CHART IIA. RECOMMENDED TOTAL 10 YEAR FUNDING FOR ROBOTIC COMPONENT TECHNOLOGIES



RANKING OF SERVICE TASKS

SERVICE TASK	WEIGHTING FACTOR
1. STEAM GENERATOR MAINTENANCE	1.0
2. VALVE AND PIPE REPLACEMENT	0.8
3. COMPONENT REPLACEMENT	0.7
4. REFUELING SERVICE	0.5
5. IN-SERVICE INSPECTION	0.3
6. FILTER CHANGING	0.3
7. SURVEILLANCE	0.2
8. UNDERWATER OPERATIONS	0.2
9. WASTE HANDLING	0.2
10. GENERAL PLANT DECONTAMINATION	0.2

TABLE 5.1 ESTIMATE OF IMPORTANCE OF ROBOTIC SYSTEM CHARACTERISTICS FOR NUCLEAR SERVICE TASKS I_{ij}

Robot Characteristic (i)	Service Task (j)									
	1	2	3	4	5	6	7	8	9	10
1. Multiple Task Capability	10	7	10	5	2	2	3	3	3	7
2. Level of Mach. Intelligence	8	4	4	8	5	2	10	5	4	5
3. Time Efficient Operation	10	5	5	7	3	2	2	2	2	2
4. Unstructured Task Level	6	8	7	5	2	3	2	8	3	9
5. Dexterity	8	8	7	3	8	3	3	8	2	5
6. Portability & Mobility	6	10	8	4	5	8	10	10	5	10
7. Precision	8	6	7	4	2	4	1	2	2	2
8. Load Capacity	8	10	5	4	2	4	1	2	3	3
9. Reliability	7	5	5	8	5	6	6	7	3	5
10. Obstacle Avoidance	5	10	7	5	5	2	3	9	2	6
11. Force Sensing	6	7	5	3	2	2	3	5	3	4
12. Smoothness of Operation	5	5	5	4	1	2	2	2	3	3
13. Operational Envelope	5	4	4	4	6	3	1	10	3	5
14. Vision	5	5	5	5	2	5	7	6	3	5

TABLE III

**RANKING OF CRITERIA FOR
SYSTEM OPERATION OF ENERGY SYSTEM
ROBOTICS APPLICATIONS**

CHARACTERISTIC	NORMALIZED RANKING
1. MULTIPLE TASK CAPABILITY	10.0
2. PORTABILITY AND MOBILITY	8.5
3. LEVEL OF MACHINE INTELLIGENCE	7.1
4. UNSTRUCTURED TASK LEVEL	7.0
5. GEOMETRIC DEXTERITY	7.0
6. RELIABILITY	6.8
7. TIME EFFICIENT OPERATION	6.6
8. LOAD CAPACITY	6.2
9. PRECISION	5.9
10. OBSTACLE AVOIDANCE	4.8
11. FORCE SENSING	4.0
12. VISION	3.0
13. OPERATIONAL ENVELOPE	2.5
14. SMOOTHNESS OF OPERATION	2.4

Table III

RANKING OF CRITERIA FOR SYSTEM OPERATION OF
ENERGY SYSTEM ROBOTICS APPLICATIONS

Characteristic	Normalized Ranking
1. Multiple Task Capability	10.0
2. Portability and Mobility	8.5
3. Level of Machine Intelligence	7.1
4. Unstructured Task Level	7.0
5. Geometric Dexterity	7.0
6. Reliability	6.8
7. Time Efficient Operation	6.6
8. Load Capacity	6.2
9. Precision	5.9
10. Obstacle Avoidance	4.8
11. Force Sensing	4.0
12. Vision	3.0
13. Operational Envelope	2.5
14. Smoothness of Operation	2.4

CHART III. RANKING OF CRITERIA FOR SYSTEM OPERATION

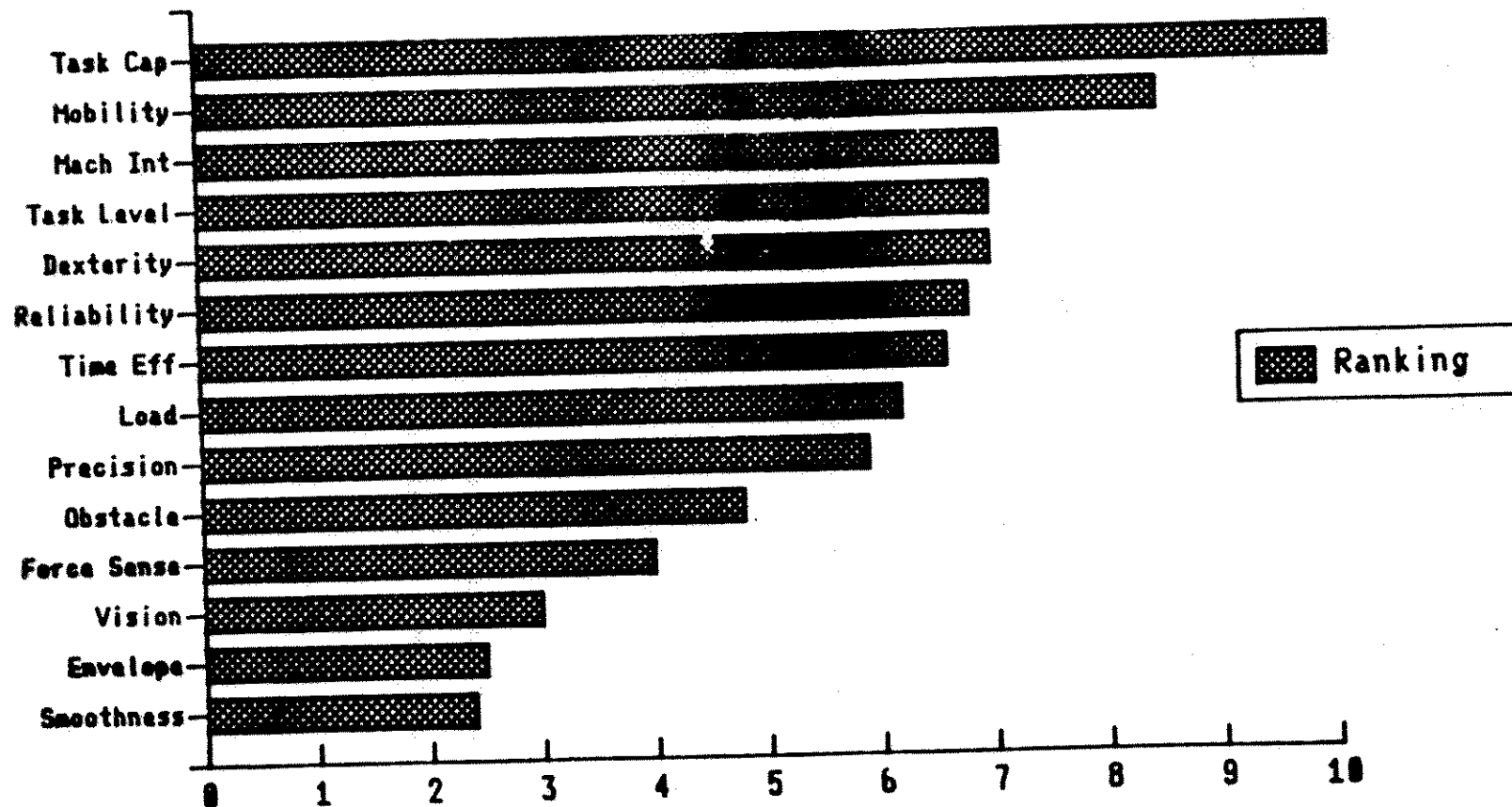
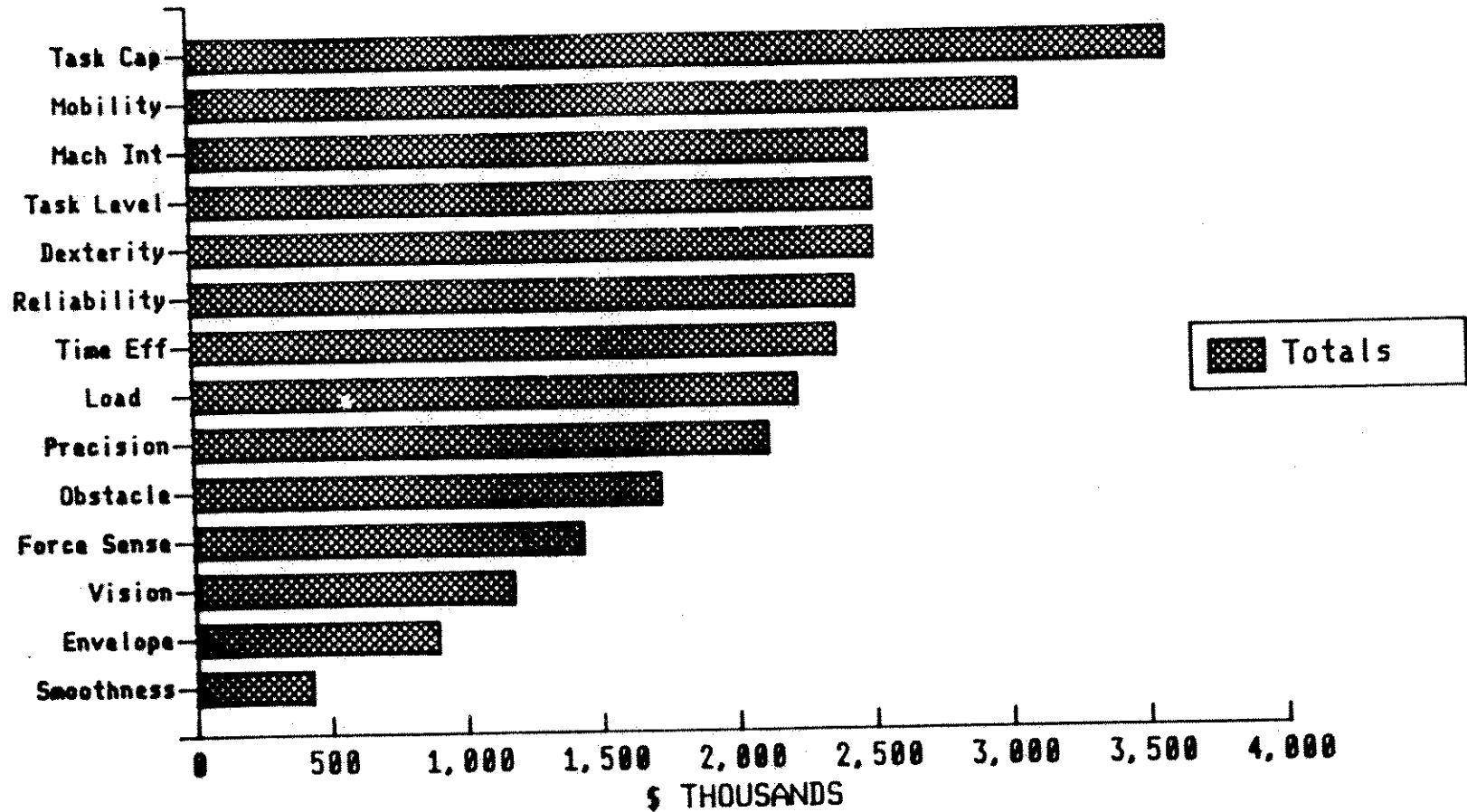


Table IIIA

RECOMMENDED YEARLY FUNDING FOR SYSTEM CAPABILITIES
IN THE NEAR, MIDDLE, AND LONG TERM (\$ Thousands)

Characteristic	<u>Level I-R&D</u>		<u>Level II-Adv Devlpmt</u>			<u>Level III - Demonstration</u>	
	Near	Middle	Near	Middle	Long	Middle	Long
1. Multiple Task	100	200	50	125	167	167	250
2. Portability & Mobility	85	170	42	106	142	142	212
3. Machine Intelligence	71	142	35	84	118	118	177
4. Unstructured Task	70	140	35	86	116	116	175
5. Geometric Dexterity	70	140	35	86	116	116	175
6. Reliability	68	136	34	85	114	114	170
7. Time Eff. Operation	66	132	33	82	110	110	165
8. Load Capacity	62	124	31	77	103	103	155
9. Precision	59	118	29	78	98	98	148
10. Obstacle Avoidance	48	96	24	60	80	80	120
11. Force Sensing	40	80	20	50	62	62	100
12. Vision	30	60	15	37	50	50	75
13. Operational Envelope	25	50	13	31	41	41	62
14. Smoothness of Operation	12	24	12	30	40	40	60
Yearly Average Total	818	1636	414	1022	1277	1277	2045

CHART IIIA. RECOMMENDED TOTAL 10 YEAR FUNDING FOR ROBOTIC SYSTEM



LIST OF ROBOT PROTOTYPES FOR ENERGY SYSTEM APPLICATIONS

Prototype	Description	Ranking
1. Dual Arm Remotely Operated Vehicle (ROV)	The most capable of all systems for maintenance on unstructured tasks, mobility may be provided by tracks.	10
2. HEAVY DUTY TRANSPORT ROV	Unit capable of transporting other maintenance systems or modules and supplies needed to perform remote operations - may be equivalent of a legged-climbing system.	7
3. MEDIUM SCALE MAINTENANCE ROBOT ARM	Versatile work horse robot for a wide range of precision operations (60"). Perhaps made of modules with up to 12-DOF.	6
4. CHERRY PICKER CONFIGURATION	A combination in series of the large and medium scale robots (50 ft and 5 ft).	4
5. SPIDERTYPE ROBOT	A small light weight walking-climbing robot for surveillance, inspection, and supply of light material.	3
6. SMALL PLATFORM MAINTENANCE ROBOT	A small manipulator (15") to work on delicate assembly operations transported by the spider robot.	2

CHART IV. RANK OF ROBOT PROTOTYPES FOR ENERGY SYSTEM APPLICATIONS

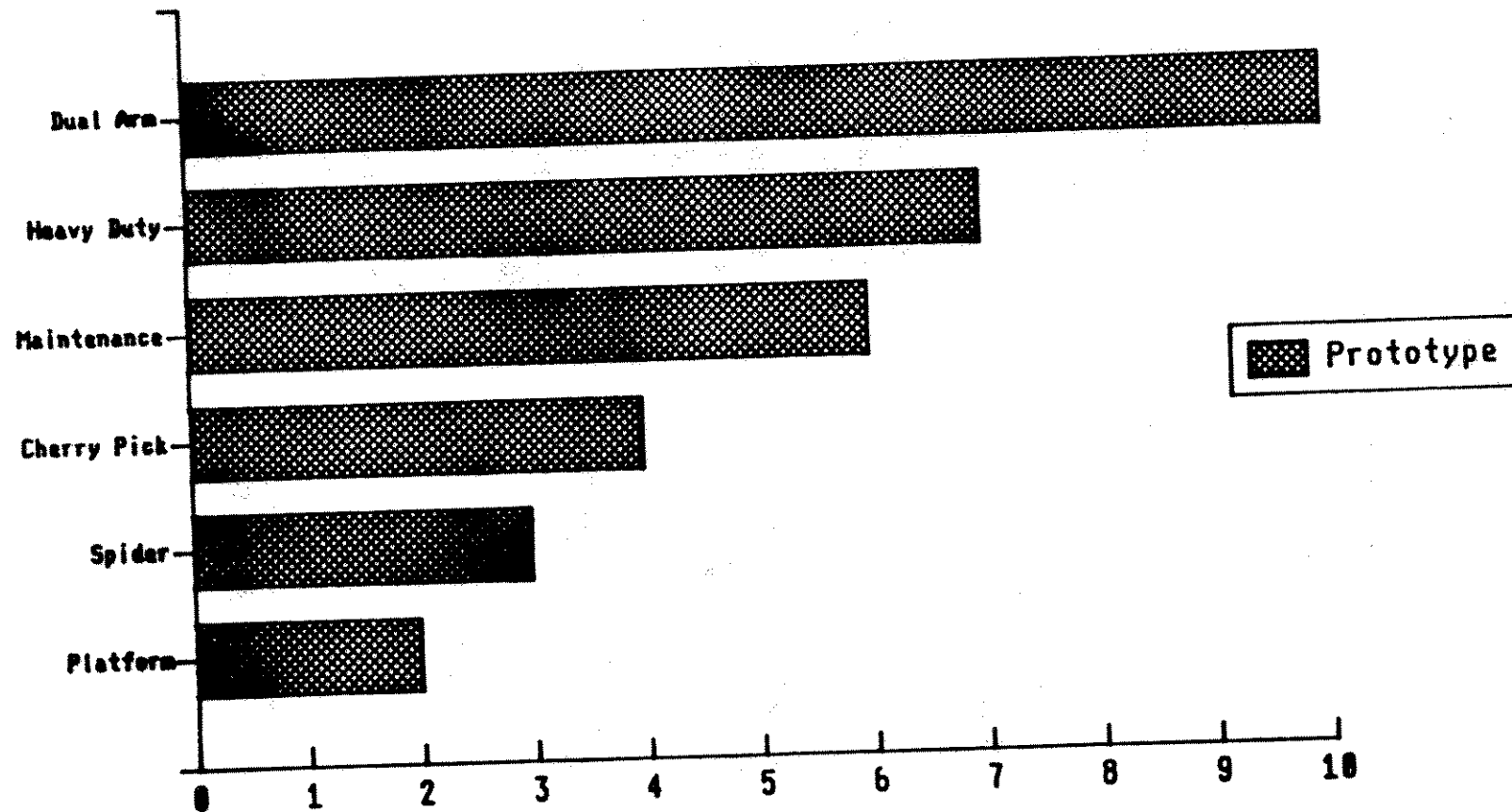


TABLE IVA

**RECOMMENDED YEARLY FUNDING FOR
ROBOTIC PROTOTYPE DEMONSTRATION FOR
ENERGY SYSTEM APPLICATIONS (\$K)**

	<u>Level II</u> <u>Adv. Devlpmt</u>		<u>Level III</u> <u>Demonstration</u>	
	<u>Middle</u>	<u>Long</u>	<u>Middle</u>	<u>Long</u>
1. Dual Arm ROV	2000	1000	1000	3000
2. Heavy Duty Transport ROV	1400	700	700	2100
3. Medium Scale Maintenance Robot Arm	1200	600	600	1800
4. Cherry Picker Configuration	800	400	400	1200
5. Spider Type Robot	600	300	300	600
6. Small Platform Maintenance Robot	400	200	200	600
	-----	-----	-----	-----
Yearly Average Totals	6400	3200	3200	9600

CHART IVA. RECOMMENDED TOTAL 10 YEAR FUNDING FOR ROBOT PROTOTYPE DEMONSTRATIONS

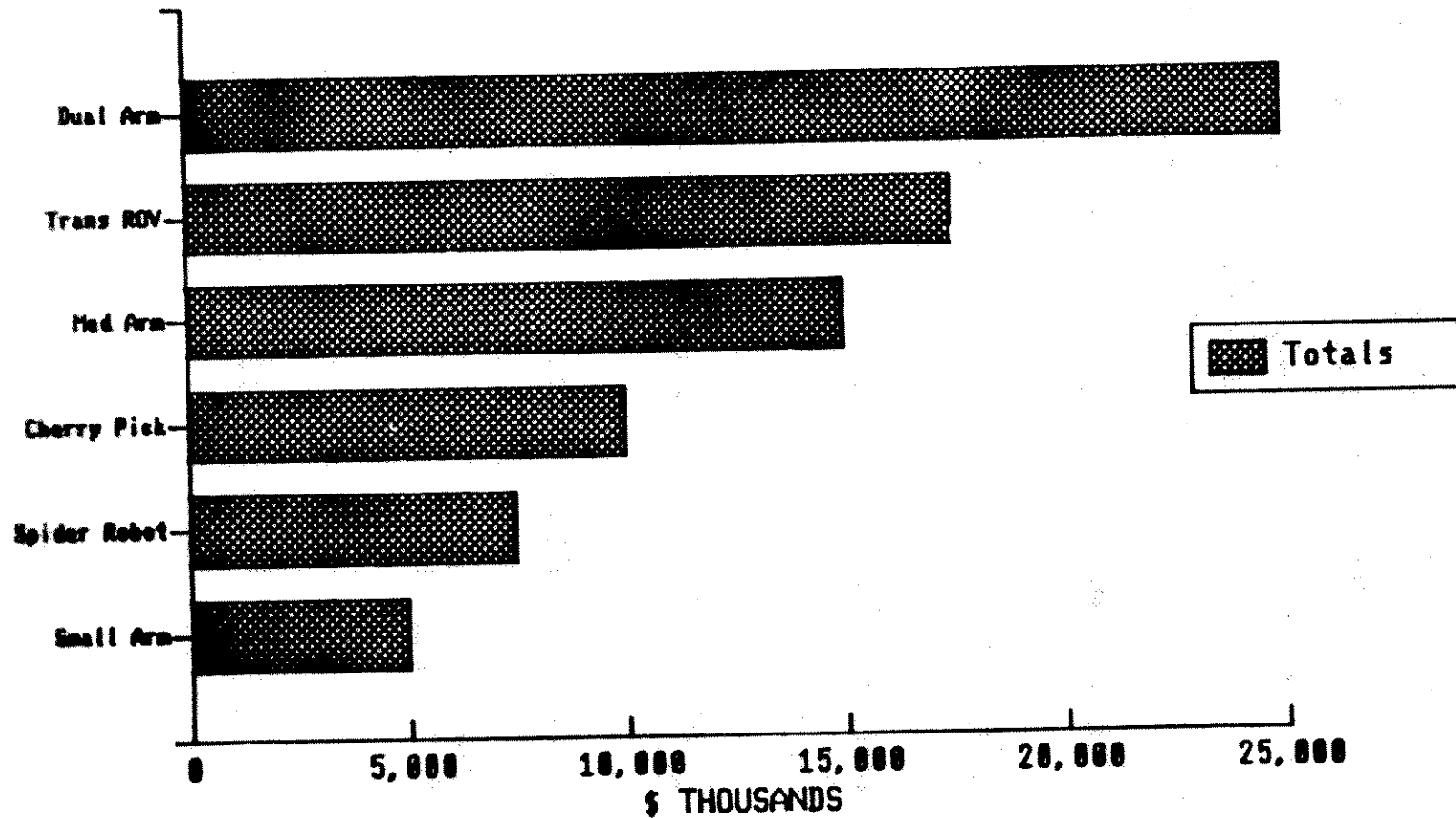


TABLE V
OVERALL RECOMMENDED YEARLY FUNDING (\$K)

Phase/ Component Tech	<u>Level I - R&D</u>		<u>Level II - Adv Devlpmt</u>			<u>Level III-Demo</u>	
	Near	Middle	Near	Middle	Long	Middle	Long
Component Technologies	1,836	---	---	4,014	2,007	---	---
System Technologies	818	1,636	414	1,022	1,277	1,277	2,045
Prototypes	---	---	---	6,400	3,200	3,200	9,600
Overall Yearly Average Total	2,654	1,636	414	11,436	5,700	4,477	11,645
OVERALL TOTAL	7,962	4,908	1,242	34,308	22,800	13,431	46,580

TEN-YEAR PROGRAM TOTAL

\$131,231

CHART V. OVERALL PLAN TO ESTABLISH ROBOTIC SYSTEMS FOR REMOTE ENERGY OPERATIONS

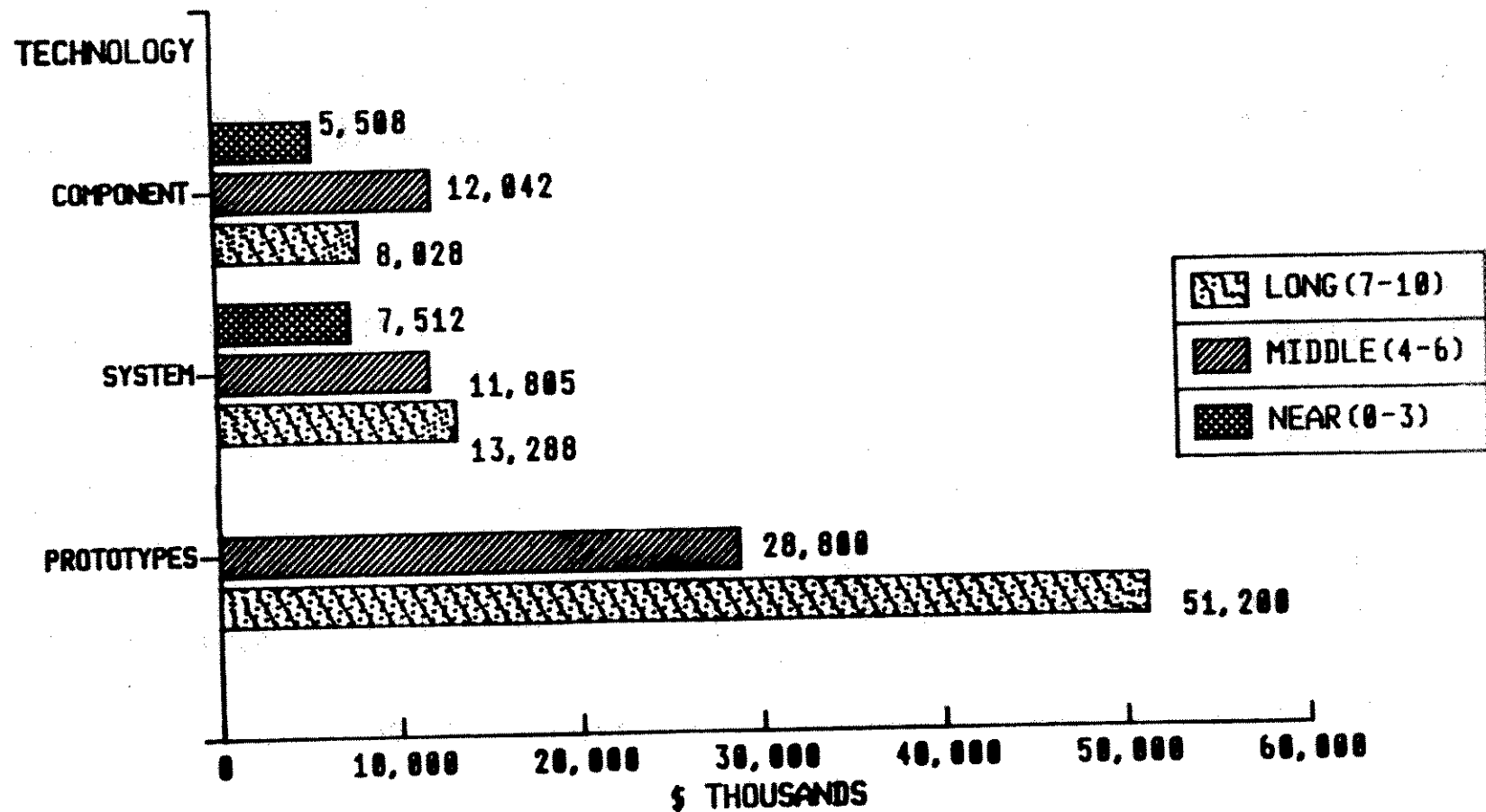
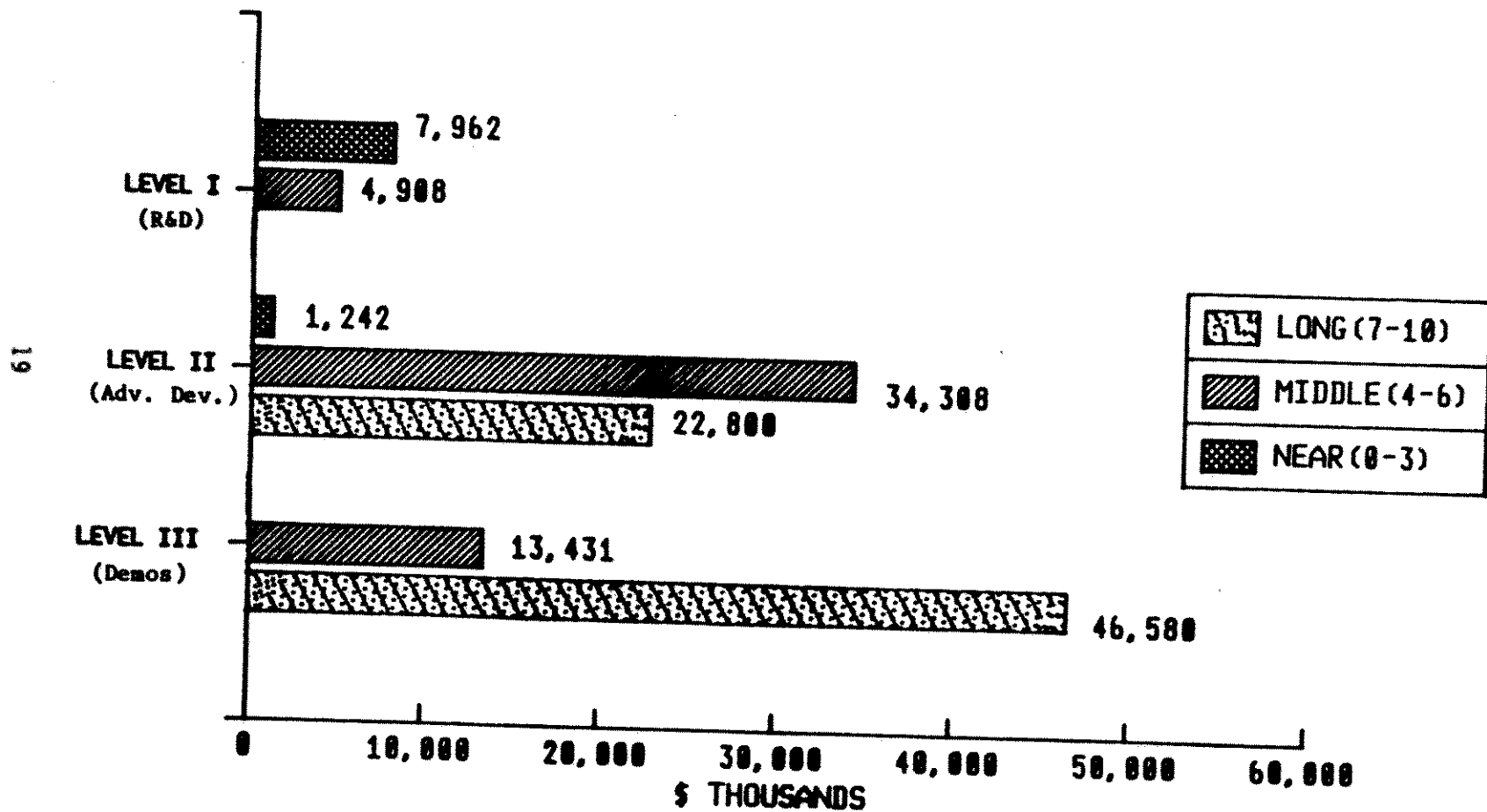


CHART VA. OVERALL LEVEL OF FUNDING FOR 10 YEAR ROBOTIC TECHNOLOGY PROGRAM



**20 YEAR FORECAST OF NASA ROBOTICS
REQUIREMENTS FOR SPACE EXPLORATION**

NOVEMBER 28, 1989

DEL TESAR/ UNIVERSITY OF TEXAS

20 Year Forecast of NASA Robotics Requirements for Space Exploration

from

Consortium of
Texas Research Universities

University of Texas at Arlington
University of Texas at Austin
Texas A&M University
Rice University

Convener: D. Tesar
512-471-3039

September 11, 1989

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RESEARCH PRINCIPALS

TEXAS UNIVERSITY ROBOTICS CONSORTIUM

The following principals have agreed to work toward a consortium associated with robotics to jointly pursue funded projects of common interest to develop advanced technology for various applications associated with space, human augmentation, manufacturing, etc.

1. Professor Richard Volz
 Chairman
 Computer Science Department
 Texas A&M University
 College Station, Texas 77843
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2. Professor George Kondraske
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 Industrial Engineering
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FAX: (817) 273-2548

3. Professor Rui J. P. de Figueiredo
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4. Professor Delbert Tesar
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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

PROPOSED RESEARCH, DEVELOPMENT AND DEMONSTRATION PROGRAM

Analysis Format

The consortium* of four Texas universities was asked to make a rough estimate of the requirements to support an RDD program

R - Research
D - Development
D - Demonstration

before deployment associated with Lunar and Mars exploration and expected surface facilities development. The goal was to rank 4 categories numerically:

Parametric Requirements
Prototypes (suggested)
Component Technologies
Robotic Characteristics.

The ranking was performed by comparing each of these categories to a representative group of applications which cover a broad range of space operations. Each application was weighted according to its importance; the categories were then compared to the application set in a matrix format and ranked from 1 to 10 (10 being the highest ranking). Each subcategory ranking was then multiplied by the corresponding application weighting factor. These weighted rankings were added together and normalized to create a final ranking of each subcategory (from 1 to 10), which gives an indication of the importance of that subcategory. The funding levels estimated for a category are based on the ranking of its subcategories.

On this ranking format, a yearly funding plan can be structured for a 20 year program. The results of this analysis are given in a series of tables and charts for quick review.

Suggested Program Plan

The proposed technology program to establish robotics as an element of the Lunar and Mars missions would be built as a combination of university, industry, and government lab activities. NASA may be able to leverage technology from other programs

* This team was convened by D. Tesar. Much of the program material has been organized by M. Butler, a MSc graduate student at the University of Texas at Austin.

(such as in NBS, DARPA, DOD logistics, DOD battlefield systems, etc.), to use the NASA FTS prototype development as a springboard, and to some extent benefit from work being pursued in industrial robotics. Careful review, however, will lead to the conclusion that these efforts are either far too small or they are not far-reaching enough. Frequently, some component technologies are frozen at levels 10 to 15 years before expected space flight. The critical issue for NASA is the availability of the total system and the corollary issue of cost effectiveness.

A fully deployed space exploration system will be of unusual complexity, far exceeding that of nuclear reactors, which are operational (available) only 67% of the time. Maintenance, repair, supply, tech mods, etc. for a deployed system will require a system* of robotic devices capable of performing routine to emergency functions either autonomously or through teleoperation for enhanced system availability, reliability, safety, and reduced cost.

The following is a sketch of a required technology development program for three phases at 7, 14, and 20 years into the future, with recommended levels of funding to make it possible for NASA to establish and manage a program of sufficient magnitude to achieve the requirements for space operations associated with Lunar and Mars exploration missions. It deals only with the operation of the robotic system and its interfaces with the overall NASA Lunar and Mars systems (i.e., the required database operations, expert systems for mission control, and AI for mission decision-making are all outside the purview of this program).

The program is defined at three levels. The first level deals directly with the tech base in terms of 14 component technologies, which should be developed in the first 14 years of the program. The second level deals with system operation (and 14 associated robotic characteristics), some of which will require the full 20 years to develop. Finally, the third level deals directly with prototype development over several generations for a finite number (10) of suggested distinct prototype robotic systems.

Overall, the 20 year RDD program will require \$1.88 billion with the following breakdown (see Table 9):

Tech Base - 20%
Development - 45%
Demonstration - 35%

Level I: Tech Base for Component Technologies for Space Robotic Systems

Fourteen component technologies have been identified which adequately represent the total robot system:

Man-Machine Interface
End-effectors
Actuator Modules
Sensor Technologies
etc.

* See listed references at the end of this executive summary.

Their ranking in importance is given in Table 4. The recommended level of funding for component development on a yearly basis will be proportional to these rankings. The near term phase will cover years 1-7; the middle term will cover years 8-14. It is unlikely that it will be necessary to continue tech base development in Level I beyond year 14. The recommended level of funding in phases I and II is given in Table 6. The 14 year funding for the tech base is recommended to be \$375 million over 14 years.

Level II: Quality of Operation of System Technologies for Space Operations

Fourteen criteria for system operation:

Multiple Task Capability
Machine Intelligence
Precision
Portability and Mobility
Reliability
etc.

have been used to establish the overall quality of operation. They are given with their ranking in Table 5. The near, middle, and long term recommended levels of funding are given in Table 7. The 20 year funding for space robotics development is recommended to be \$839 million.

Level III: Prototype Development to Meet Specific Applications for the Lunar and Mars Missions

Table 3 is an abbreviated list of possible robot prototypes:

Medium Space Platform Robot
Dual Arm ROV Module
Cherry Picker
Large Space Platform Robot
Autonomous Transport Robot
etc.

that might be developed for the Lunar and Mars missions; a rough ranking of their overall importance is included. Generally, prototype development should be delayed until the middle term. However, some early research activity may be warranted for design purposes. The recommended level of yearly funding is given in Table 8; the last 13 years of the program associated with prototype development is recommended to be \$664 million.

Summary

Table 10 summarizes the yearly average totals of the program. The total cost of the 20 year program becomes \$1.878 billion. Such a program would, of course, put the United States in the place of having the best future robotic technology in the world and assure that the Lunar and Mars missions would be able to dramatically improve the availability of space by establishing its reliability, safety, effectiveness, and value to the nation.

References

- [1] Tesar, D., "Next Generation of Technology for Robotics," Report from the University of Texas at Austin, February, 1985.
- [2] Tesar, D., "An Assessment of the Development and Application Potential for Robots to Support Space Station Operations," Report from the University of Texas at Austin, September, 1985.
- [3] Tesar, D., "Thirty-Year Forecast: The Concept of a Fifth Generation of Robotics - The Super Robot," ASME Transactions Manufacturing Review, Vol. 2, No. 1, pp. 16-25, March, 1989.
- [4] Tesar, D., and Butler, M., "A Generalized Modular Architecture for Robotic Structures," ASME Transactions Manufacturing Review, Vol. 2, No. 2, pp. 91-118, June, 1989.

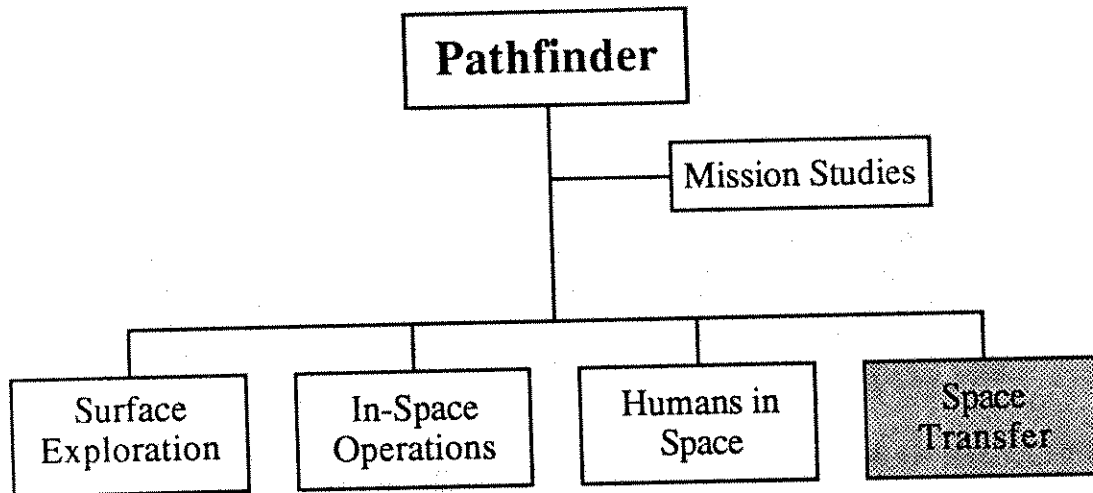
OVERVIEW OF APPLICATIONS OF SPACE ROBOTICS FOR THE LUNAR AND MARS MISSIONS

Why Space Robotics?

- 1) **Safety of humans in space:** Exposure of humans to hazardous environments such as EVA, nuclear and hazardous chemical fuels handling, and high-radiation zones should be minimized.
- 2) **Increased human productivity:** Routine and/or hazardous tasks can be automated, and crew time-consuming EVA preparation can be minimized by the use of robots.
- 3) **Performance of tasks that are infeasible for humans:** Robots can greatly enhance human capabilities for such tasks as moving large structures, capturing spinning satellites, and controlling complex systems.
- 4) **Enabling new missions to other planets:** Mobility and manipulation aids for manned missions and automated systems for complex unmanned missions, e.g., Mars rover/sample return, will provide new capabilities.

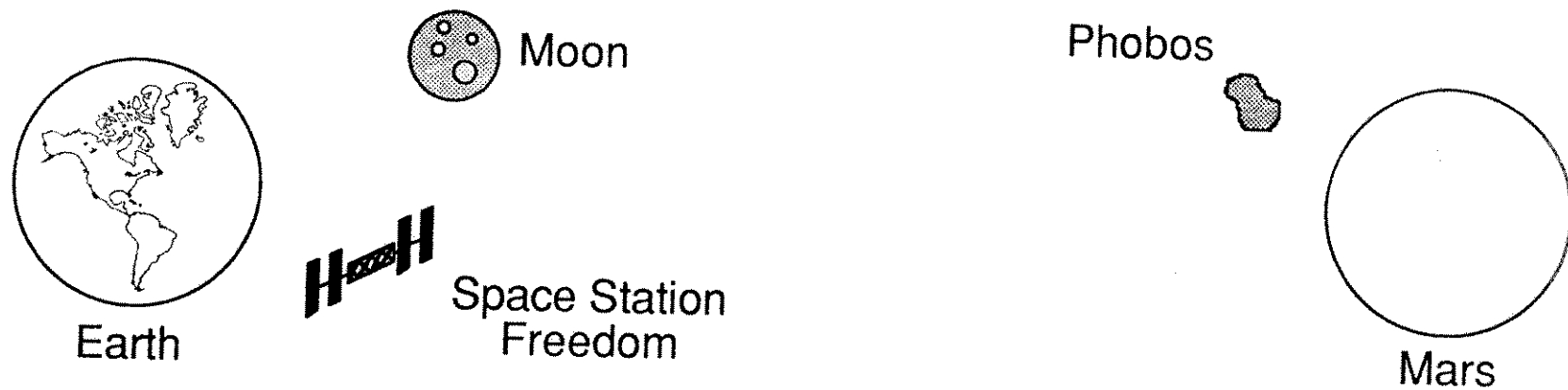
From: "Space Technology to Meet Future Needs", Committee on Advanced Space Technology, Aeronautics and Space Engineering Board, Commission on Engineering and Technical Systems, National Research Council, 1987.

Pathfinder Program

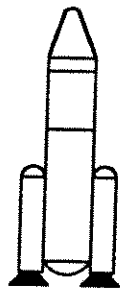


Robotic technology is crucial to three of the four program areas targeted for improvement by Pathfinder:

- Surface Exploration
 - Planetary Rover
 - Sample Acquisition, Analysis, and Preservation
 - Autonomous Lander
- In-Space Operations
 - Autonomous Rendezvous and Docking
 - In-Space Assembly and Construction
 - Cryogenic Fuel Depot
- Humans in Space
 - Extravehicular Activity/Suit
 - Space Human Factors



NASA OEXP Case Studies for Human Exploration of the Solar System (FY 1988)



- 1) Human Expedition to Phobos
- 2) Human Expeditions to Mars
- 3) Lunar Observatory
- 4) Lunar Outpost to Early Mars Evolution

ROBOTIC SPACE APPLICATIONS

Space Operations

- 1) Assembly of Space Structures
- 2) Space Station Maintenance and Repair
- 3) Satellite Servicing and Repair
- 4) Hazardous Manufacturing and Laboratory Experiments
- 5) Maintenance of Robots

Space Exploration

- 6) Orbital Nodes
- 7) Phobos Expedition
- 8) Mars Expedition
- 9) Lunar Outpost/Fuel Production
- 10) Robotic Solar System Exploration

Robotic Tasks for Orbital Nodes

- In-Space Assembly and Construction
 - Cargo and Crew Ships
 - Propellant Depots
- Cryogenic Fluid Storage/Transfer
- Autonomous/Supervised Rendezvous and Docking
- Payload Servicing
- Maintenance & Repair

Robotic Tasks for Phobos Expedition

- Orbital Node Requirements
- Autonomous/Supervised Rendezvous and Docking
- Manned Exploration of Phobos (~ 0 g)
 - Excursion Vehicle
 - Anchoring to Surface
 - Sample Acquisition
 - Conduction of Experiments (Atmospheric, Geophysical, etc.)
- Robotic Exploration of Mars Surface (~ 1/3 g)
 - Teleoperated Mars Rovers
 - Mapping
 - Sample Acquisition
 - Conduction of Experiments (Atmospheric, Geophysical, etc.)
- Maintenance & Repair of Transports & Equipment
- Cryogenic Fluid Storage/Transfer

Robotic Tasks for Mars Expeditions

- Orbital Node Requirements
- Autonomous/Supervised Rendezvous and Docking
- Manned Exploration of Mars Surface (~1/3 g)
 - Mars Rovers
 - Surface and Sub-Surface Mapping
 - Sample Acquisition, Site Selection
 - Conduction of Experiments (Atmospheric, Geophysical, etc.)
- Manned Exploration of Phobos and Deimos (~0 g)
 - Excursion Vehicle
 - Anchoring to Surface
 - Sample Acquisition
 - Conduction of Experiments (Atmospheric, Geophysical, etc.)
- Maintenance & Repair of Transports & Equipment
- Cryogenic Fluid Storage/Transfer

Robotic Tasks for Lunar Outpost/Fuel Production

- Digging, Transporting, and Processing of Regolith (Lunar Soil)
 - Excavation of Lunar Surface
 - Preparation of landing sites
 - Foundations for housing, experimental structures
 - Cover housing structures with regolith for protection from radiation
 - Exploitation of Lunar Resources
 - Reduction of oxides in soil yields oxygen for fuel, life support
 - Helium-3 for future nuclear fusion reactors on Earth
 - Processing of regolith to create fiberglass or bricks for lunar construction
- Assembly and Construction of Lunar Structures
 - Housing
 - Experimental Equipment
(Optical & Radio Telescopes, Seismographs, Etc.)
 - Fuel Production & Power Plants
- Exploration of Lunar Surface (~ 1/6 g)
 - Manned/Teleoperated Lunar Rovers
 - Surface and Sub-Surface Mapping
 - Sample Acquisition, Site Selection
 - Conduction of Experiments (Atmospheric, Geophysical, etc.)
- Automation Robots
 - Automation of Processing Plants
 - Maintenance & Repair of Lunar Structures & Equipment
- Cryogenic Fluid Storage/Transfer

Robotic Tasks for Robotic Solar System Exploration

- Possible Orbital Node Requirements
- Precursor Missions
 - *Mars Observer*
 - *Lunar Observer*
- Sample Return Missions
 - *Mars Rover and Sample Return (MRSR)*
 - *Comet Nucleus Sample Return (CNSR)*
- Observation Missions
 - *Galileo* (to Jupiter)
 - *Magellan* (to Venus)
 - *Comet Rendezvous Asteroid Flyby (CRAF)*
 - *Cassini* (to Saturn)
- Tasks Include:
 - Autonomous Rover
 - Autonomous/Supervised Rendezvous and Docking
 - Sample Acquisition
 - Maintenance and Repair
 - Cryogenic Fuel Transfer

STATUS OF TECHNOLOGY FOR SPACE ROBOTICS DEVELOPMENT

ENVIRONMENT FOR SPACE ROBOTICS DEVELOPMENT

TECHNOLOGY

- 1. Extreme Light Weight Requirement**
- 2. High Levels of Autonomy**
- 3. High Level of Human Intervention in Some Cases**
- 4. Versatility, Dexterity, Reliability, Modularity, etc.**

ROBOT APPLICATIONS FOR SPACE STATION

I. ASSEMBLY OF SPACE STRUCTURES

- 1. Handling of Large Modules**
- 2. Precise Sub-Assembly Tasks**
- 3. Precision Welding and Forming**
- 4. Precision Light Machining**

II. SPACE STATION MAINTENANCE AND REPAIR

- 1. Continuous Inspection Required**
- 2. 40% of Repairs to Be Unplanned**
- 3. Unstructured Task Environment**
- 4. Precision Under Disturbance**

III. SATELLITE SERVICING AND REPAIR

- 1. 75 Missions / Year**
- 2. Unstructured Tasks**
- 3. Some Precision Work Under Disturbance**
- 4. Docking Dynamics Critical**

IV. HAZARDOUS MANUFACTURING AND LABORATORY EXPERIMENTS

- 1. Cluttered Environment in Module**
- 2. Clean Room Atmosphere**
- 3. Absolute Stability Desired**
- 4. Furnace Renovation Critical**

V. MAINTENANCE OF ROBOTS

- 1. Software Adaptability to Change in Parameters**
- 2. Modularity for Maintainability**
- 3. Module Replacement for Technology Up-Date**
- 4. Duality in Critical Maintenance Operations**

ROBOTIC OPERATIONS ASSOCIATED WITH THE SPACE STATION

I. LONG TERM IN-DEPTH FUNCTIONS

- CLEAN ROOM OPERATIONS (Experimental and Manufacturing)
- SELF MEASUREMENT OF LARGE SPACE STATION DIMENSIONS
- SPACE STATION ASSEMBLY
- SPACE STATION REPAIR AND MAINTENANCE
- ORBITING SATELLITE REPAIR AND MAINTENANCE

II. COMPLEX DYNAMIC MOTION TASKS

- DOCKING AND GRAPPLING MANEUVERS
- REACTIONLESS OPERATIONS
- STABILIZATION BY APPENDAGE MOTION
- RIGIDIZATION
- CATCHING AND STORING SPACE DEBRIS
- THROWING AND JUMPIING
- DUAL ROBOT OPERATIONS

III. UNIT PROCESSES FOR SPACE STATION OPERATION

- OPERATE SIMPLE MECHANISMS
latches, cranks, slides, handles
- JOINING AND FASTENING
fitting, force fit connectors, spot welding, forming, bolting, screwing, locking, coiling, riveting, electron beam welding
- PRECISION MACHINING
grinding, sanding, brushing, drilling, routing, trimming, cutting
- HANDLING
parts transfer, limp materials, slippery materials, warehousing
- AUTOMATED INSPECITON
seam tracking, surface flaws, meteorite damage, etc. on solar arrays, thermal radiators, windows, mirrors....

TECH BASE ISSUES FOR ROBOTICS

I. LIGHTWEIGHT

1. Robots Are Limber
2. Must Be Made Electronically Rigid
3. Requires Complete Parametric Model
4. Level of Control Far Beyond Present Capability

II. PRECISION UNDER DISTURBANCE

1. Precision Light Machining
2. Real Time Dynamic Model
3. Adaptive Control
4. Feedforward Compensation

III. MAN-MACHINE INTERFACE

1. Need Increases with Better Technology
2. Should Be Kinesthetic (Analog)
3. Force Feedback Essential
4. Generic Universal Manual Controller

IV. DYNAMICS OF DOCKING

1. Shock to Station Undesirable
2. Satellite Spin and Wobble is COMplex
3. Presently Time Required Is Unacceptable
4. Sophisticated Manipulator Dynamics Required

V. LEVEL OF TECHNOLOGY REQUIRED

1. Far Beyond Today's Industrial Robot
2. Geometry Must Be More Generic (Parallel)
3. Dynamic Control Technology Grossly Inadequate
4. Balance of Electrical and Mechancial Essential

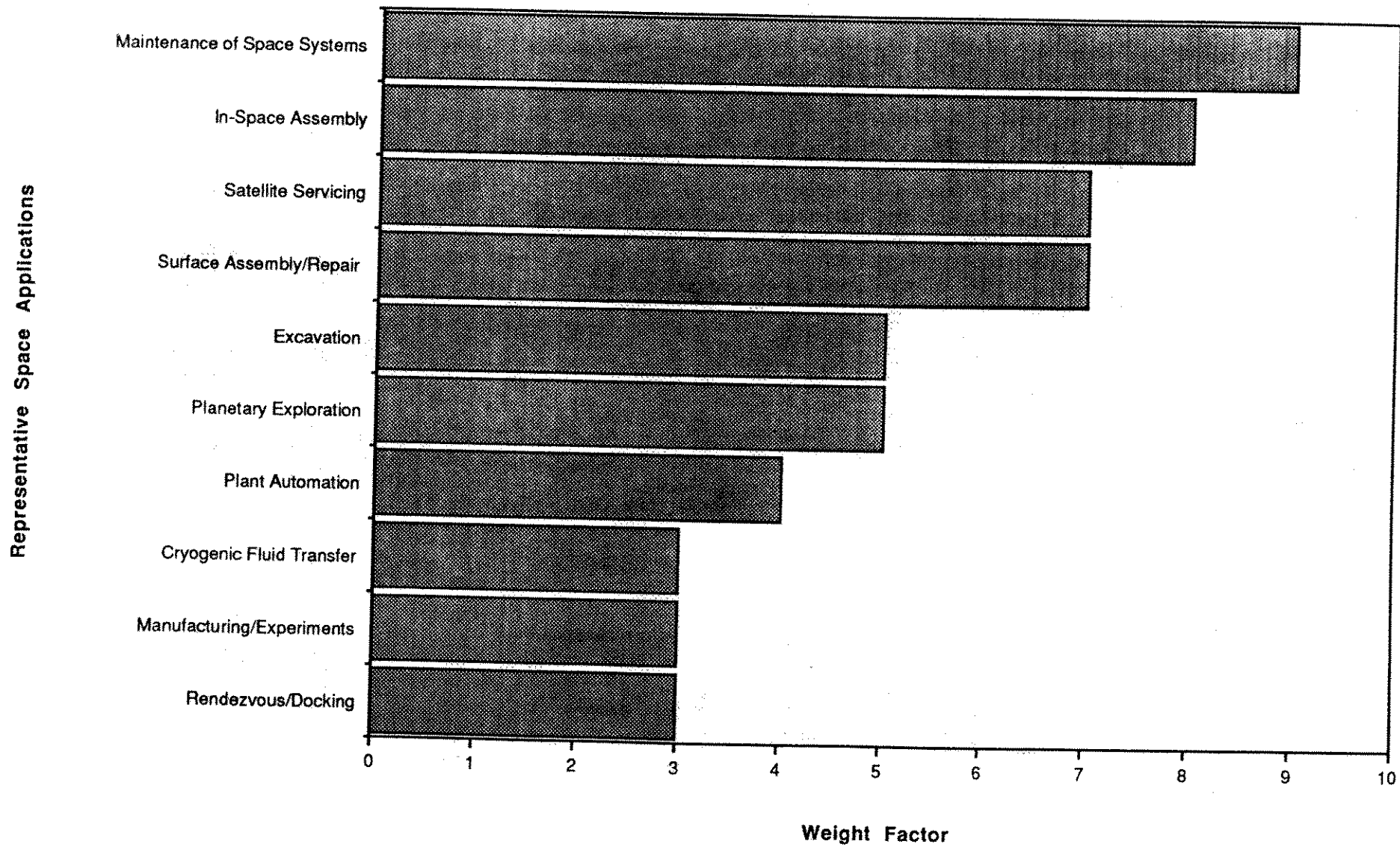
NUMERICAL RANKING OF SPACE ROBOTICS

- **Applications**
- **Parametric Requirements**
- **Prototypes**
- **Component Technologies**
- **System Characteristics**

**TABLE 1. REPRESENTATIVE APPLICATIONS
FOR ROBOTICS IN SPACE**

<u>APPLICATIONS</u>	<u>DESCRIPTION</u>	<u>WEIGHT FACTOR</u>
1. Maintenance and Repair of Space Systems	Repair Tasks on Space Station and Other Spacecraft, Processing Plants, etc.	9
2. In-Space Assembly and Construction	Assembly of Space Station, Orbital Nodes, Fuel Depots, Large Spacecraft, etc.	8
3. Assembly and Repair of Surface Structures	Habitats, Processing Plants, Power Plants, Experimental Equipment, etc.	7
4. Satellite Servicing	In Situ Refueling, Repair, Battery and Module Replacement, etc.	7
5. Planetary Surface Exploration	Lunar and Mars Rovers, Sample Acquisition	5
6. Excavation	Mining of Lunar Soil, Preparation of Landing Sites, Roads, etc.	5
7. Plant Automation	Automation of Processing and Power Plants on Planetary Surface	4
8. Autonomous/Supervised Rendezvous and Docking	Control of Spacecraft Docking Procedures	3
9. Hazardous Manufacturing and Experiments	Scientific Experiments on Space Shuttle, Planetary Surface	3
10. Cryogenic Fluid Storage/Transfer	Transfer and Storage of Hydrogen, Oxygen, and Other Liquid Fuels	3

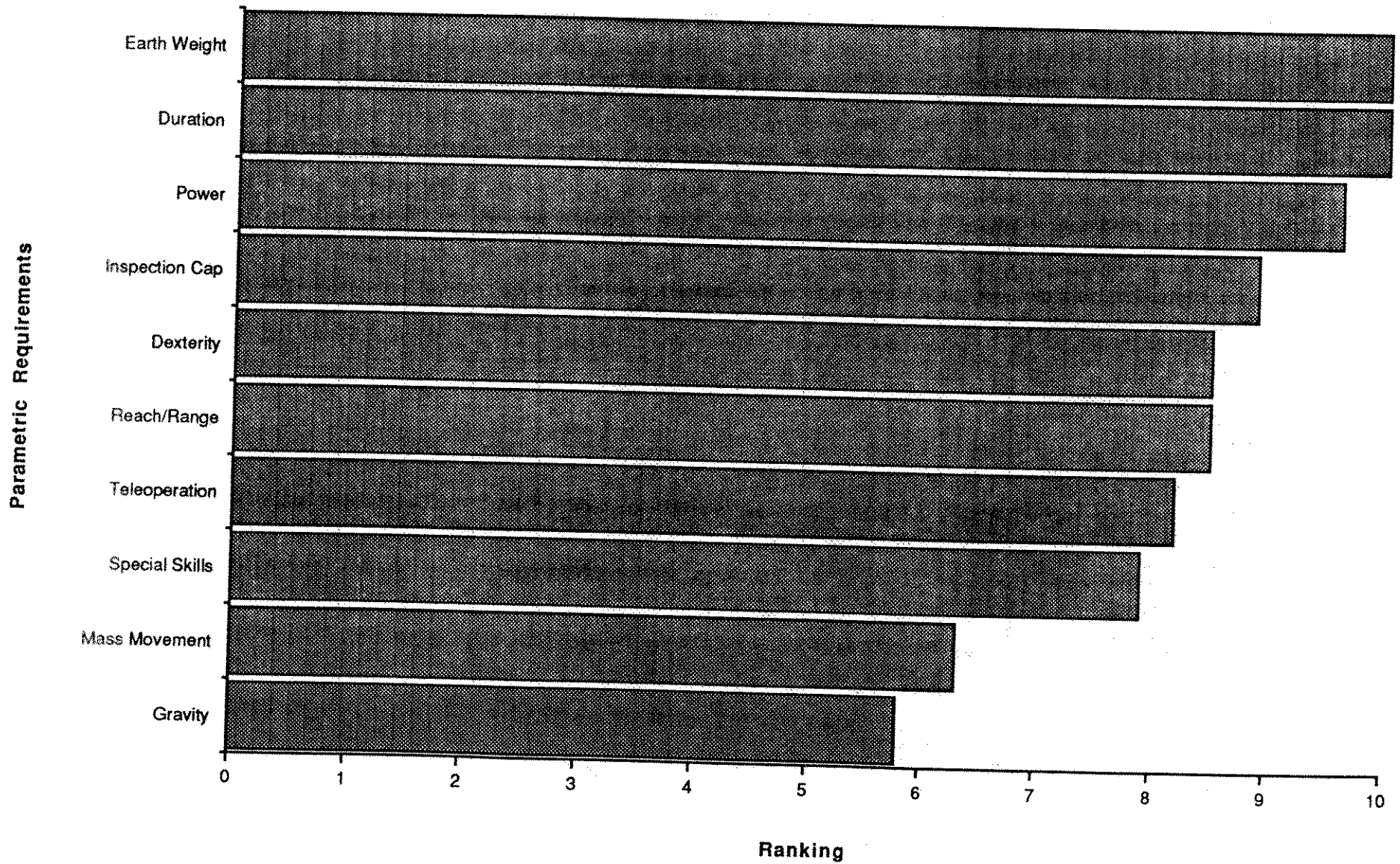
Chart 1. Weighting of Representative Space Applications



**TABLE 2. PARAMETRIC REQUIREMENTS FOR
ROBOTIC SPACE APPLICATIONS**

<u>PARAMETRIC REQUIREMENT</u>	<u>DESCRIPTION</u>	<u>RANKING</u>
1. Duration of Functionality	1 hour, 1 day, 1 week, 1 month, 1 year, 10 years	10.0
2. Earth Weight Equivalent	1 oz, 1 lb, 10 lb, 100 lb, 1000 lb, 10,000 lb	10.0
3. Power Requirements	0.1 Watt up to 100 MW	9.6
4. Inspection Capability	CCTV, Machine Vision, etc.	8.9
5. Reach/Range Capability	5 ft., 50 ft. 1 mile, 100 miles, 1000 miles, 1,000,000 miles	8.5
6. Dexterity Capability for Retrieval and Assembly	Geometric Shape, Amorphous Shape, Pick and Place, Constrained Motion	8.5
7. Teleoperation Distance (Time Lag Issues)	< 10', < 100', < 1 mile, < 1000 mi, < 1,000,000 mi, < 10,000,000 mi	8.2
8. Special Skills	Drilling, Coring, Fluid Transfer, Material Processing, Ranging, Flight, etc.	7.9
9. Mass Movement Capacity	1 oz, 1 lb, 100 lb, 500 lb, etc.	6.3
10. Gravitational Environment	0 g (Space, Phobos) 1/6 g (Lunar Surface) 1/3 g (Mars Surface) 1 g (Earth)	5.8

Chart 2. Ranking of Parametric Requirements for Space Applications



Matrix 2.

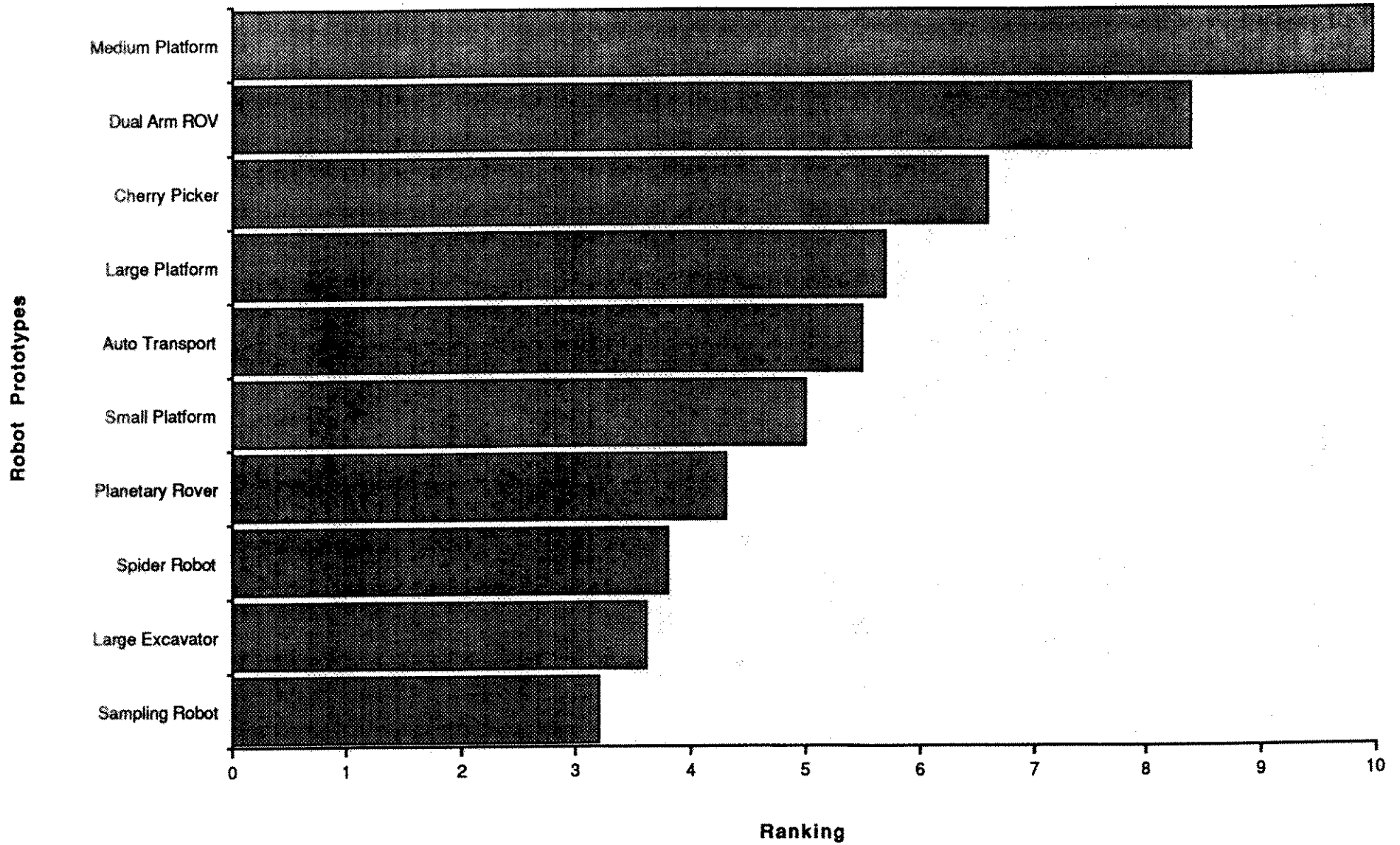
Estimates of Importance of Parametric Requirements for Space Operations

Parametric Requirements	In-Space Assembly & Construction	Maintenance & Repair of Space Systems	Cryogenic Fluid Storage/Transfer	Autonomous/Supervised Rendezvous & Docking	Assembly & Repair of Surface Structures	Excavation	Planetary Surface Exploration	Hazardous Manufacturing & Experiments	Satellite Servicing	Plant Automation
1. Gravitational Environment	6	5	2	3	3	4	3	3	4	4
2. Inspection Capability	7	8	5	4	5	3	9	4	8	4
3. Mass Movement Capacity	6	3	2	7	5	6	3	2	5	3
4. Reach/Range Capability	9	7	3	3	7	4	7	2	6	3
5. Dexterity Capability	7	8	4	4	8	3	4	4	6	5
6. Special Skills	4	8	2	2	9	3	4	3	8	4
7. Teleoperation Distance	5	7	6	5	5	3	9	3	8	3
8. Duration of Functionality	5	6	5	5	8	9	8	6	8	9
9. Earth Weight	6	6	4	4	8	10	8	5	8	8
10. Power Requirements	4	7	5	4	8	10	9	5	9	2

**TABLE 3. ROBOT PROTOTYPES FOR
SPACE APPLICATIONS**

	<u>PROTOTYPE</u>	<u>DESCRIPTION</u>	<u>RANKING</u>
1.	Medium Space Platform Robot	Work Horse Robot (60 in.) for Precision Operations	10.0
2.	Dual Arm ROV Module	Free Flying Supply & Maintenance System for Unstructured Tasks	8.4
3.	Cherry Picker	Large (60 ft.) & Medium (60 in.) Robots in Series	6.6
4.	Large Space Platform Robot	Deployment Robot (60 ft.) for Large Motions	5.7
5.	Autonomous Transport Robot	Inventory & Parts Handling for Processing and Power Plants	5.5
6.	Small Space Platform Robot	Small Robot (15 in.) for Delicate Assembly	5.0
7.	Planetary Rover	Vehicle for Exploration of Lunar or Mars Surface	4.3
8.	Spider Robot	Six-Legged Module for Continuous Inspection	3.8
9.	Large Excavation Robot	Large Robot (10 ft.) for Site Preparation & Mining	3.6
10.	Sample Acquisition Robot	Local Soil Sampling, Analysis & Preservation	3.2

Chart 3. Ranking of Robot Prototypes for Space Applications



Matrix 3.
Estimates of Importance of Robot Prototypes for Space Operations

Robot Prototype	In-Space Assembly & Construction	Maintenance & Repair of Space Systems	Cryogenic Fluid Storage/Transfer	Autonomous/Supervised Rendezvous & Docking	Assembly & Repair of Surface Structures	Excavation	Planetary Surface Exploration	Hazardous Manufacturing & Experiments	Satellite Servicing	Plant Automation
1. Dual Arm ROV Module	8	8	2	3	6	2	2	4	9	6
2. Cherry Picker	9	7	1	1	6	1	1	1	6	2
3. Planetary Rover	1	3	2	1	4	3	10	2	1	3
4. Medium Space Platform Robot	8	8	6	5	8	4	6	6	8	6
5. Large Excavation Robot	1	1	1	1	6	10	1	1	1	1
6. Large Space Platform Robot	9	3	4	4	4	3	1	2	4	2
7. Autonomous Transport Robot	4	2	5	1	5	6	3	4	2	8
8. Sample Acquisition Robot	1	1	1	1	2	3	9	2	1	2
9. Spider Robot	3	3	3	2	3	2	2	3	2	3
10. Small Space Platform Robot	3	6	2	2	3	1	1	4	6	3

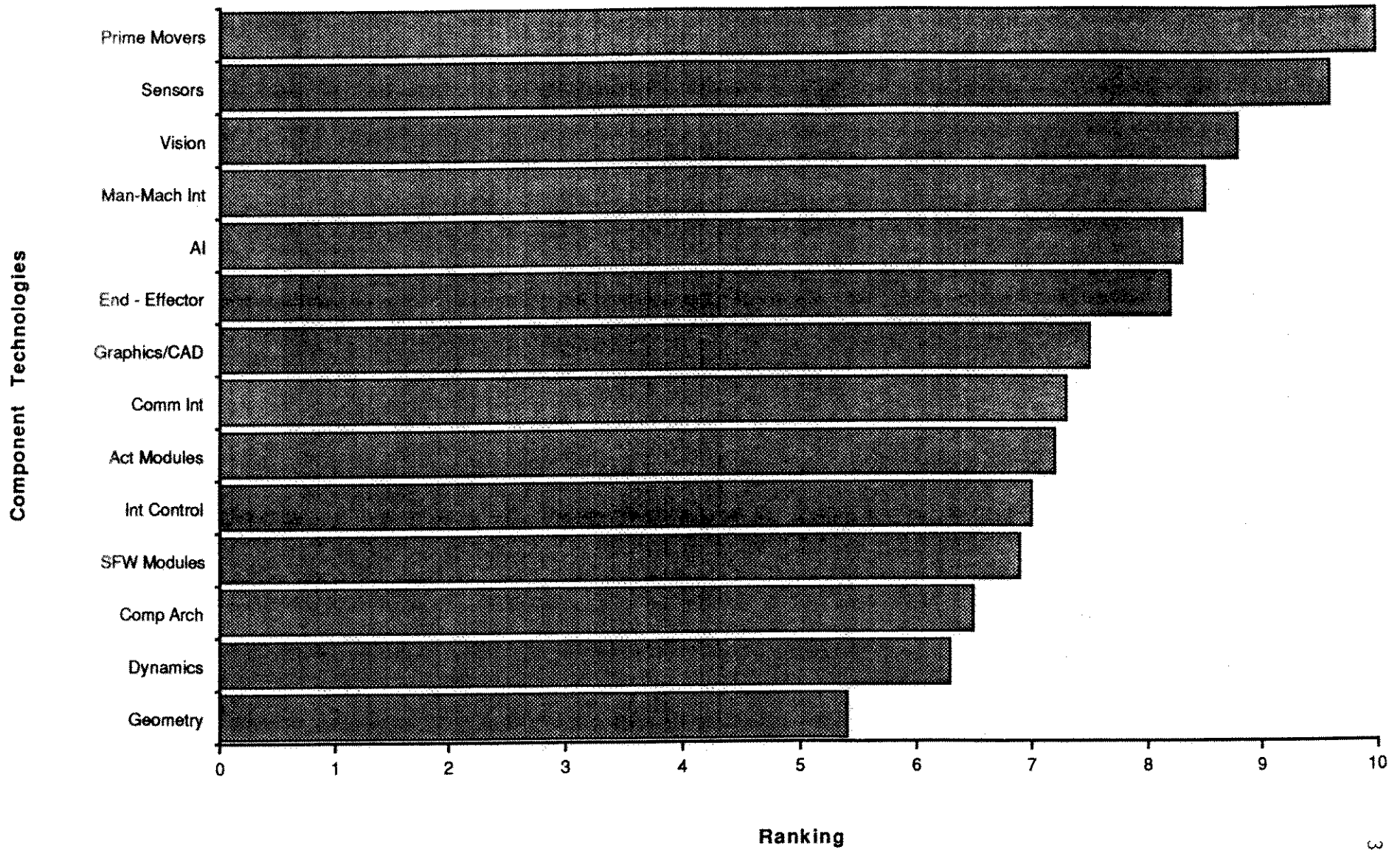
**TABLE 4. RANKING OF
COMPONENT TECHNOLOGIES
FOR SPACE APPLICATIONS**

<u>COMPONENT TECHNOLOGY</u>	<u>DESCRIPTION</u>	<u>RANKING</u>
1. Prime Movers	Muscles of Robot; Electrical, Hydraulic, Pneumatic	10.0
2. Sensor Technology	Awareness of System, Process, Quality Control; Touch, Force, Proximity, etc.	9.6
3. Vision	Computer Analyzed Visual Data for Inspection and Position Referencing	8.8
4. Man-Machine Interface	Direct Bilateral Human Communication; Voice, Force, Kinesthetic, etc.	8.5
5. Artificial Intelligence	Decision Making for Multi- Layered Phenomenon	8.3
6. End Effectors	Hand of Robot; for Handling, Inspection, Welding, etc.	8.2
7. Graphics/CAD	Interactive Design, Optimization, Training	7.5

**TABLE 4. RANKING OF
COMPONENT TECHNOLOGIES
FOR SPACE APPLICATIONS (Cont.)**

<u>COMPONENT TECHNOLOGY</u>	<u>DESCRIPTION</u>	<u>RANKING</u>
8. Communication Interfaces	Interface Among All Arrays and Layers of System Components	7.3
9. Actuator Modules	Structural Units Combining Geometry and Prime Mover; Shoulder, Elbow, Wrist, etc.	7.2
10. Intelligent Control	Real Time Model to Make System Rigid, Massless, Responsive, Precise, Smooth, etc.	7.0
11. Software Modules	Portable, Hardened Packages of Algorithms and Chips for Rapid Interchangeability	6.9
12. Computer Architecture	Serial and Parallel Processors, Dedicated Processors, etc.	6.5
13. Structural Dynamics	Dynamic Loads, Vibrations, Precision, Speed, etc.	6.3
14. Structural Geometry	Workspace Reach, Dexterity, Obstacle Avoidance, etc.	5.4

Chart 4. Ranking of Component Technologies for Space Applications



Matrix 4.
Estimates of Importance of Component Technologies for Space Operations

Robotic Component Technology	In-Space Assembly & Construction	Maintenance & Repair of Space Systems	Cryogenic Fluid Storage/Transfer	Autonomous/Supervised Rendezvous & Docking	Assembly & Repair of Surface Structures	Excavation	Planetary Surface Exploration	Hazardous Manufacturing & Experiments	Satellite Servicing	Plant Automation
1. Geometry	5	7	2	2	5	1	2	3	4	2
2. Dynamics	5	6	3	8	4	3	4	3	5	3
3. Prime Movers	8	9	4	6	8	7	7	5	7	6
4. Actuator Modules	6	8	2	3	6	4	3	2	7	3
5. End Effectors	6	10	3	4	7	2	3	5	8	4
6. Graphics/CAD	7	9	2	2	8	1	2	4	7	3
7. Sensor Technology	5	9	4	5	9	5	9	5	8	5
8. Vision	4	7	4	5	8	5	10	5	8	5
9. Artificial Intelligence	5	5	4	6	8	4	9	4	7	6
10. Intelligent Control	5	7	3	6	7	3	3	3	6	3
11. Software Modules	5	7	1	5	7	2	3	4	7	3
12. Computer Architecture	5	6	2	3	6	2	4	3	7	3
13. Communication Interfaces	5	7	3	3	6	3	7	3	7	3
14. Man-Machine Interface	6	10	4	4	8	3	4	3	8	3

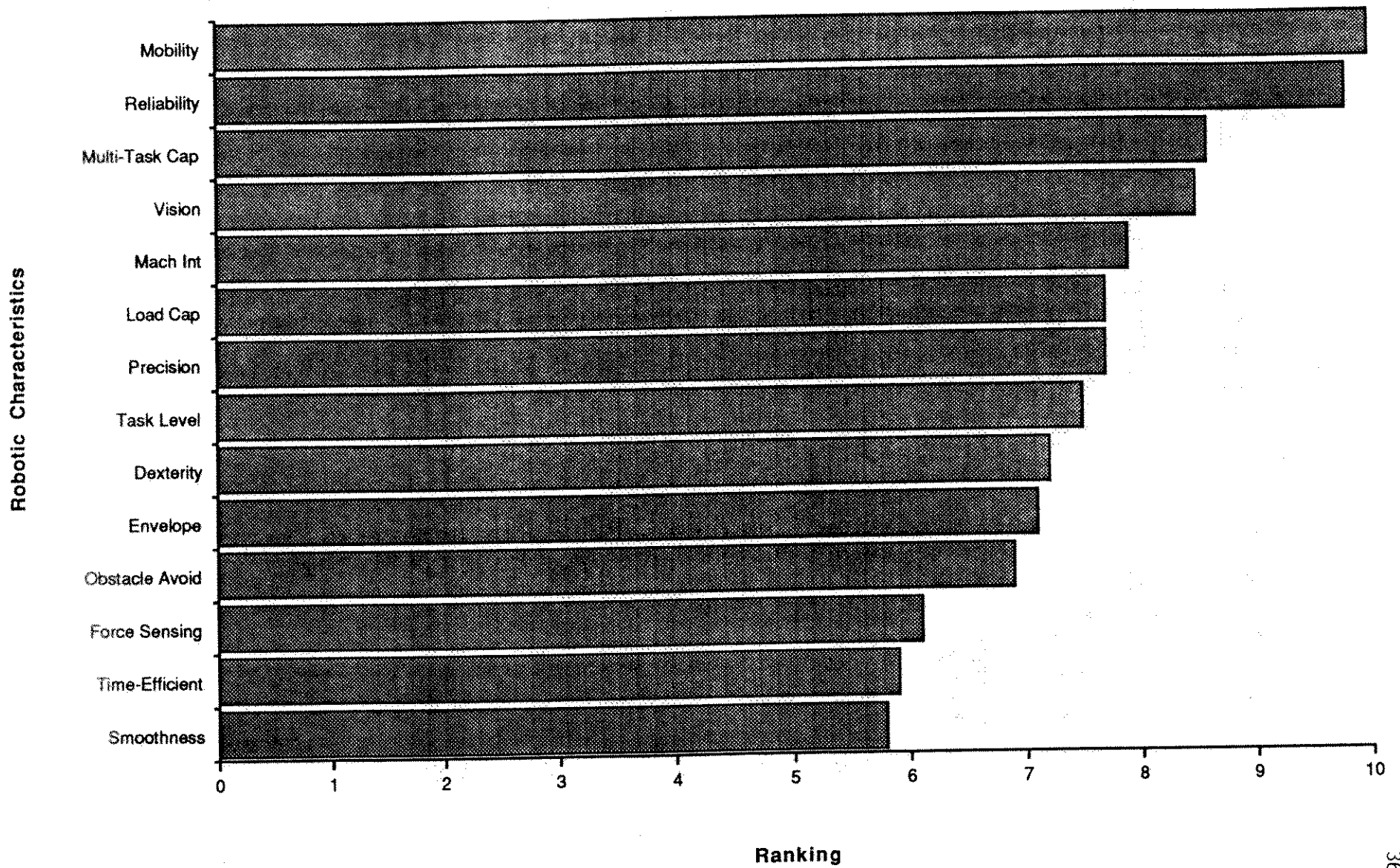
**TABLE 5. RANKING OF
ROBOTIC CHARACTERISTICS
FOR SPACE APPLICATIONS**

<u>ROBOTIC CHARACTERISTIC</u>	<u>DESCRIPTION</u>	<u>RANKING</u>
1. Portability & Mobility	Absolute Movement of Robot Base With or Without Human Assistance	10.0
2. Reliability	Failure Rate of Entire System	9.8
3. Multiple Task Capability	Number of Different Physical Tasks Feasible	8.6
4. Vision	Shape Recognition and Environment of Unit Process	8.5
5. Level of Machine Intelligence	Level of Integration of Computer Hardware, Software, AI, etc.	7.9
6. Precision	Absolute Precision of Positioning of End- Effector in World Coordinates	7.7
7. Load Capacity	Ability to Resist External Loads Without Major Deformation	7.7

**TABLE 5. RANKING OF
ROBOTIC CHARACTERISTICS
FOR SPACE APPLICATIONS (Cont.)**

<u>ROBOTIC CHARACTERISTIC</u>	<u>DESCRIPTION</u>	<u>RANKING</u>
8. Unstructured Task Level	Level of Numerical Uncertainty in Task Specification	7.5
9. Geometrical Dexterity	Effective Motion Range (Linear and Angular) of the End-Effector	7.2
10. Operational Envelope	Working Range Without Moving Shoulder or Base	7.1
11. Obstacle Avoidance	Robot and End-Effector Avoidance of Obstacles in the Work Environment	6.9
12. Force Sensing	Level of Force Awareness; Deflection Compensation Becomes Possible	6.1
13. Time-Efficient Operation	Speed of Performance Relative to Human Acting Alone	5.9
14. Smoothness of Operation	Lack of Backlash or Very Large Deflections	5.8

Chart 5. Ranking of Robotic Characteristics for Space Applications



Matrix 5.
Estimates of Importance of Robotic Characteristics for Space Applications

Robotic Characteristic	In-Space Assembly & Construction	Maintenance & Repair of Space Systems	Cryogenic Fluid Storage/Transfer	Autonomous/Supervised Rendezvous & Docking	Assembly & Repair of Surface Structures	Excavation	Planetary Surface Exploration	Hazardous Manufacturing & Experiments	Satellite Servicing	Plant Automation
1. Multiple Task Capability	7	10	2	3	9	3	5	7	10	7
2. Level of Machine Intelligence	7	10	3	4	8	3	6	5	7	5
3. Time-Efficient Operation	5	7	3	4	7	3	3	3	5	4
4. Unstructured Task Level	5	10	3	3	8	3	6	3	9	3
5. Geometric Dexterity	8	8	3	3	7	3	3	5	8	4
6. Portability & Mobility	8	9	7	3	9	8	10	7	9	8
7. Precision	7	9	5	4	8	2	4	6	8	5
8. Load Capacity	7	7	3	7	8	10	3	5	5	5
9. Reliability	7	7	7	9	9	9	9	8	8	9
10. Obstacle Avoidance	8	8	2	3	7	3	3	4	7	4
11. Force Sensing	5	7	3	5	6	4	3	3	7	2
12. Smoothness of Operation	5	6	3	9	5	3	3	3	5	5
13. Operational Envelope	9	8	3	3	8	4	3	4	5	4
14. Vision	7	9	4	5	7	5	9	4	9	5

RECOMMENDED YEARLY FUNDING

<u>Component Technologies</u>	Years	\$ (Million)
Tech Base	1-7	10.740
	8-14	16.111
Development	1-7	8.055
	8-14	24.166
<u>System Technologies</u>		
Tech Base	1-7	10.687
	8-14	16.030
Development	1-7	5.343
	8-14	16.030
	15-20	21.687
Demonstration	8-14	10.687
	15-20	21.374
<u>Prototype Technologies</u>		
Development	8-14	16.834
	15-20	28.056
Demonstration	8-14	22.444
	15-20	56.112

**Table 6. Recommended Yearly Funding for
Component Technology Development
in the Near and Middle Term (\$ Thousands)**

Component Technology	Level I - Research		Level II - Development	
	Near Term	Middle Term	Near Term	Middle Term
1. Prime Movers	\$1,000	\$1,500	\$750	\$2,250
2. Sensor Technology	\$956	\$1,434	\$717	\$2,152
3. Vision	\$884	\$1,326	\$663	\$1,990
4. Man-Machine Interface	\$848	\$1,272	\$636	\$1,909
5. Artificial Intelligence	\$825	\$1,238	\$619	\$1,857
6. End Effectors	\$823	\$1,234	\$617	\$1,851
7. Graphics/CAD	\$753	\$1,130	\$565	\$1,695
8. Communication Interfaces	\$728	\$1,091	\$546	\$1,637
9. Actuator Modules	\$717	\$1,076	\$538	\$1,614
10. Intelligent Control	\$699	\$1,049	\$524	\$1,573
11. Software Modules	\$689	\$1,033	\$517	\$1,550
12. Computer Architecture	\$645	\$968	\$484	\$1,452
13. Structural Dynamics	\$632	\$949	\$474	\$1,423
14. Structural Geometry	\$540	\$810	\$405	\$1,215
Average Yearly Total	\$10,740	\$16,111	\$8,055	\$24,166

Chart 6. Recommended Total 20 Year Funding for Robotic Component Technologies

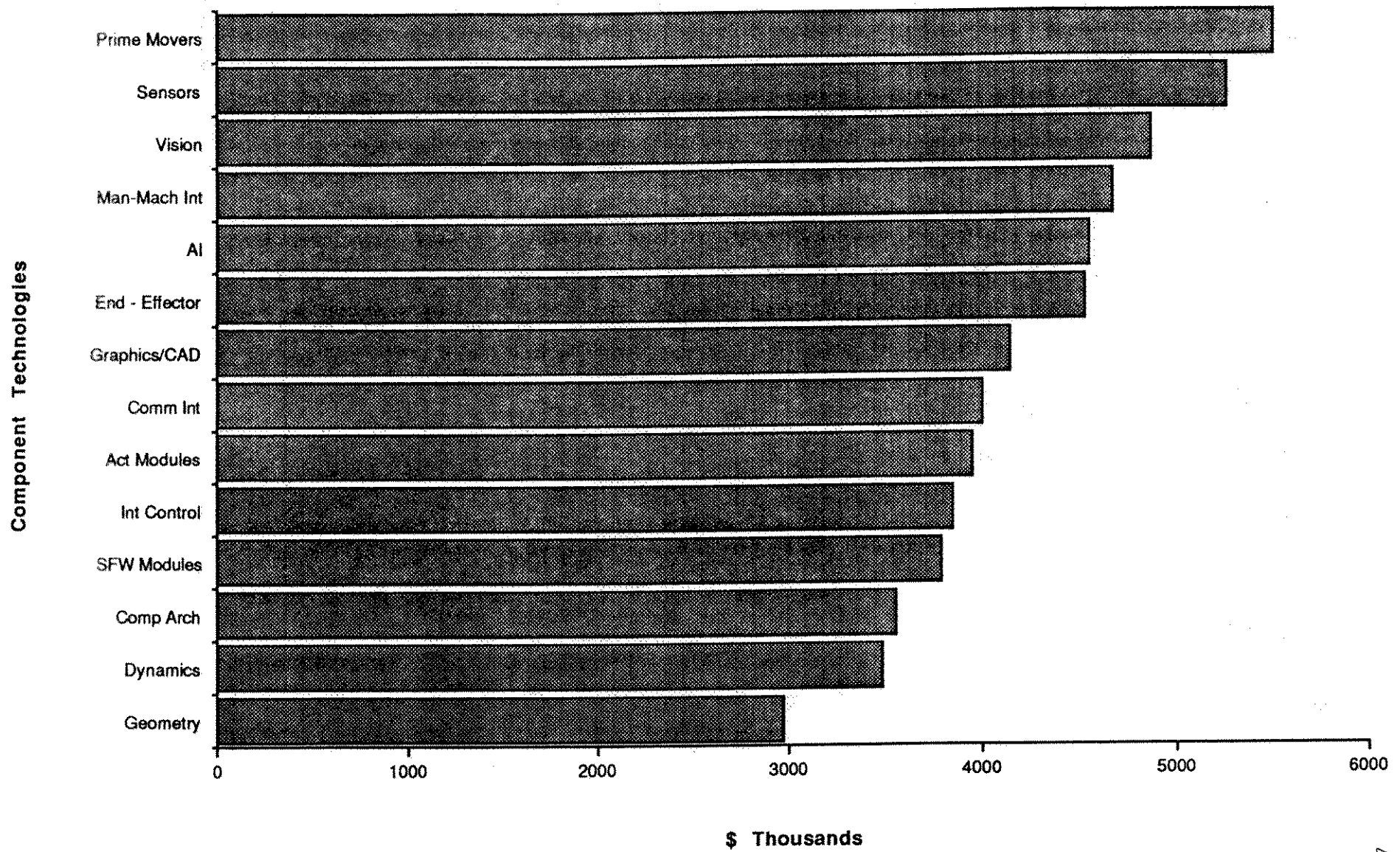


Table 7. Recommended Yearly Funding for Robotic Characteristics in the Near, Middle, and Long Term (\$ Thousands)

Robotic Characteristic	Level I - Research		Level II - Development			Level III - Demo	
	Near	Middle	Near	Middle	Long	Middle	Long
1. Portability & Mobility	\$1,000	\$1,500	\$500	\$1,500	\$2,000	\$1,000	\$2,000
2. Reliability	\$982	\$1,473	\$491	\$1,473	\$1,964	\$982	\$1,964
3. Multiple Task Capability	\$863	\$1,294	\$431	\$1,294	\$1,725	\$863	\$1,725
4. Vision	\$851	\$1,277	\$426	\$1,277	\$1,703	\$851	\$1,703
5. Level of Machine Intelligence	\$793	\$1,189	\$396	\$1,189	\$1,586	\$793	\$1,586
6. Precision	\$775	\$1,162	\$387	\$1,162	\$1,550	\$775	\$1,550
7. Load Capacity	\$766	\$1,149	\$383	\$1,149	\$1,532	\$766	\$1,532
8. Unstructured Task Level	\$750	\$1,125	\$375	\$1,125	\$1,500	\$750	\$1,500
9. Geometric Dexterity	\$721	\$1,081	\$360	\$1,081	\$1,441	\$721	\$1,441
10. Operational Envelope	\$712	\$1,068	\$356	\$1,068	\$1,423	\$712	\$1,423
11. Obstacle Avoidance	\$691	\$1,037	\$346	\$1,037	\$1,383	\$691	\$1,383
12. Force Sensing	\$608	\$912	\$304	\$912	\$1,216	\$608	\$1,216
13. Time-Efficient Operation	\$592	\$889	\$296	\$889	\$1,185	\$592	\$1,185
14. Smoothness of Operation	\$583	\$875	\$292	\$875	\$1,167	\$583	\$1,167
Average Yearly Total	\$10,687	\$16,030	\$5,343	\$16,030	\$21,374	\$10,687	\$21,374

Chart 7. Recommended Total 20 Year Funding for Robotic Characteristics

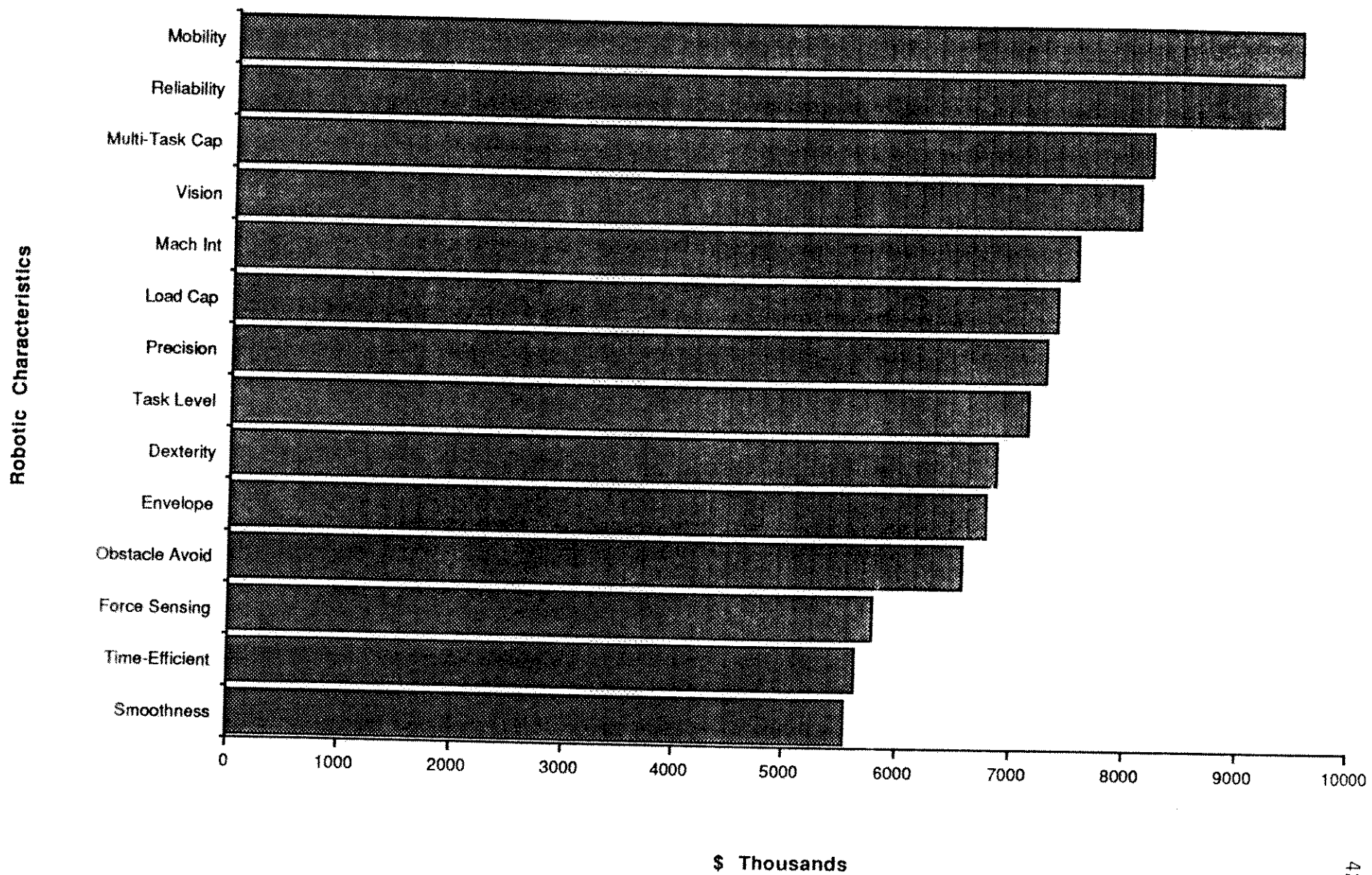
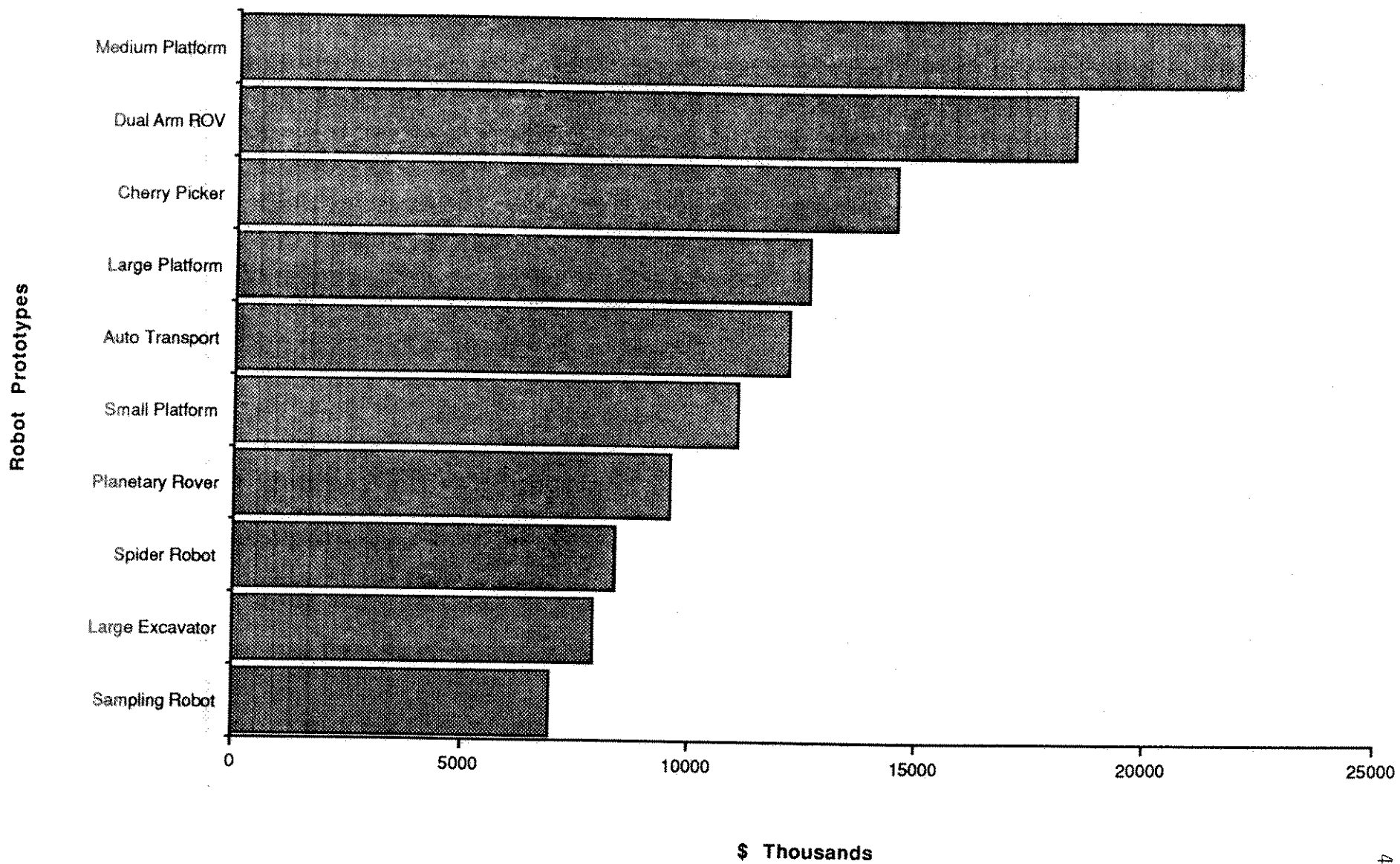


Table 8. Recommended Yearly Funding for Robot Prototype Development and Demonstration in the Middle and Long Term (\$ Thousands)

Robot Prototype	Level II - Development		Level III - Demonstration	
	Middle Term	Long Term	Middle Term	Long Term
1. Medium Space Platform Robot	\$3,000	\$5,000	\$4,000	\$10,000
2. Dual Arm ROV Module	\$2,509	\$4,182	\$3,346	\$8,365
3. Cherry Picker	\$1,979	\$3,298	\$2,638	\$6,595
4. Large Space Platform Robot	\$1,713	\$2,855	\$2,284	\$5,710
5. Autonomous Transport Robot	\$1,657	\$2,761	\$2,209	\$5,523
6. Small Space Platform Robot	\$1,504	\$2,507	\$2,005	\$5,013
7. Planetary Rover	\$1,303	\$2,172	\$1,737	\$4,343
8. Spider Robot	\$1,142	\$1,903	\$1,523	\$3,807
9. Large Excavation Robot	\$1,078	\$1,796	\$1,437	\$3,592
10. Sample Acquisition Robot	\$949	\$1,582	\$1,265	\$3,164
Average Yearly Total	\$16,834	\$28,056	\$22,444	\$56,112

Chart 8. Recommended Total 20 Year Funding for Robot Prototypes



OVERALL PROGRAM PLAN FOR 20 YEARS OF SPACE ROBOTICS DEVELOPMENT

**TECH BASE - 20%
DEVELOPMENT - 45%
DEMONSTRATION - 35%**

OVERALL COST FOR 20 YEAR PROGRAM

\$1,877,684,000

TABLE 9.
SUGGESTED PROGRAM STRUCTURE (RDD)

Tech Base: 20% over years 0-14

14 Component Technologies Make Up Total Robotic System:

Man-Machine Interface
End Effectors
Actuator Modules
Sensor Technologies
etc.

Development: 45% over years 0-20

14 Robotic Characteristics to Enhance Robot Operation and Performance:

Multiple Task Capability
Machine Intelligence
Precision
Portability & Mobility
Reliability
etc.

Demonstration: 35% over years 8-20

Prototype Designs Over Several Generations:

Medium Space Platform Robot
Dual Arm ROV Module
Cherry Picker
Large Space Platform Robot
Autonomous Transport Robot
Small Space Platform Robot
Planetary Rover
Spider Robot
Large Excavation Robot
Sample Acquisition Robot

Table 10.
Overall Recommended Yearly Funding (\$ Thousands)

	<u>Level I - Research</u>		<u>Level II - Development</u>			<u>Level III - Demo</u>	
	Near Term	Middle Term	Near Term	Middle Term	Long Term	Middle Term	Long Term
Component Technologies	\$10,740	\$16,111	\$8,055	\$24,166	--	--	--
System Capabilities	\$10,687	\$16,030	\$5,343	\$16,030	\$21,374	\$10,687	\$21,374
Prototype Development	--	--	--	\$16,834	\$28,056	\$22,444	\$56,112
Overall Average Yearly Total	\$21,427	\$32,141	\$13,398	\$57,030	\$49,430	\$33,131	\$77,486
Overall Total	\$149,989	\$224,987	\$93,786	\$399,210	\$346,010	\$198,786	\$464,916

Chart 9. Overall Level of Funding for 20 Year Robotic Technology Program for Space Applications

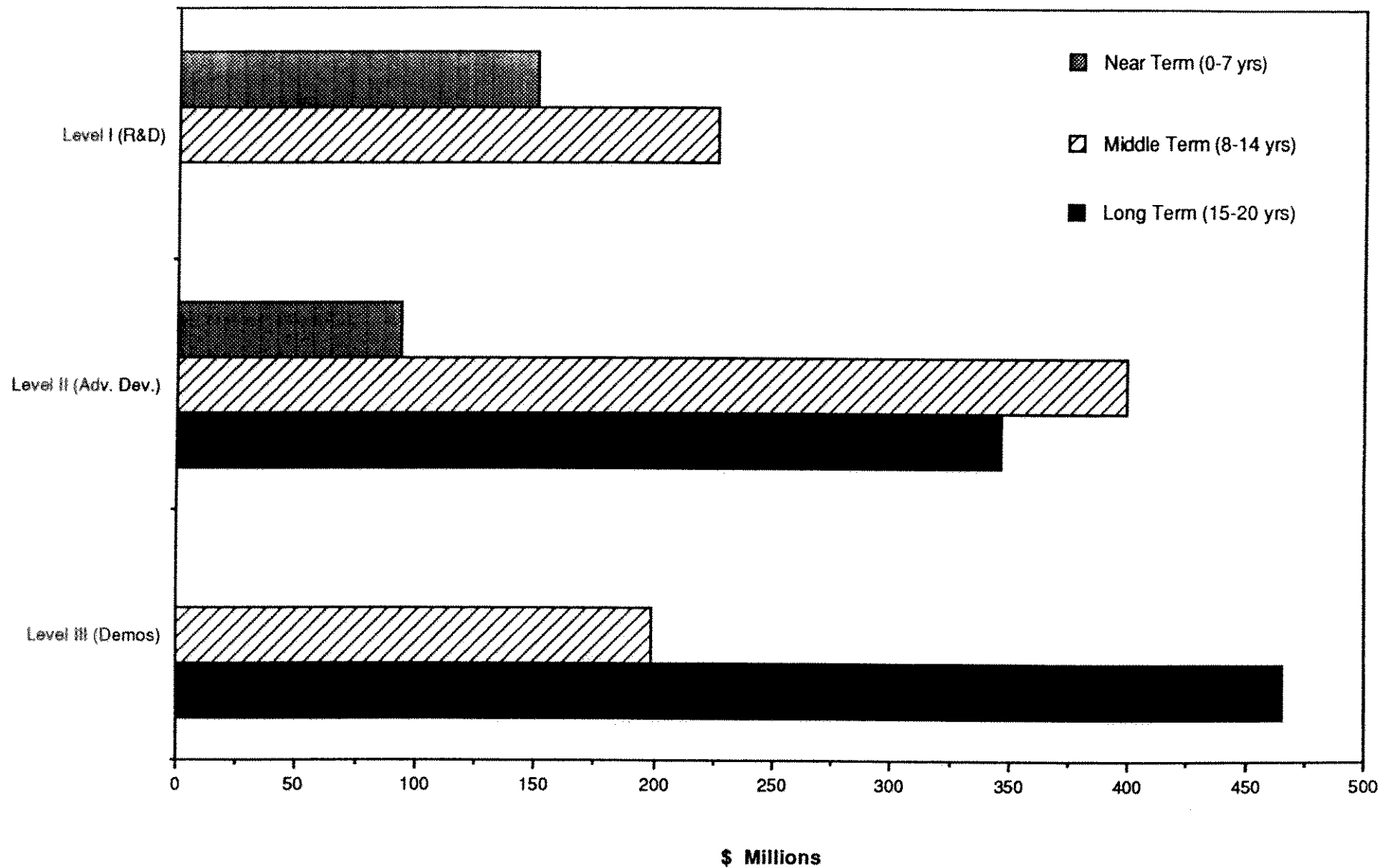
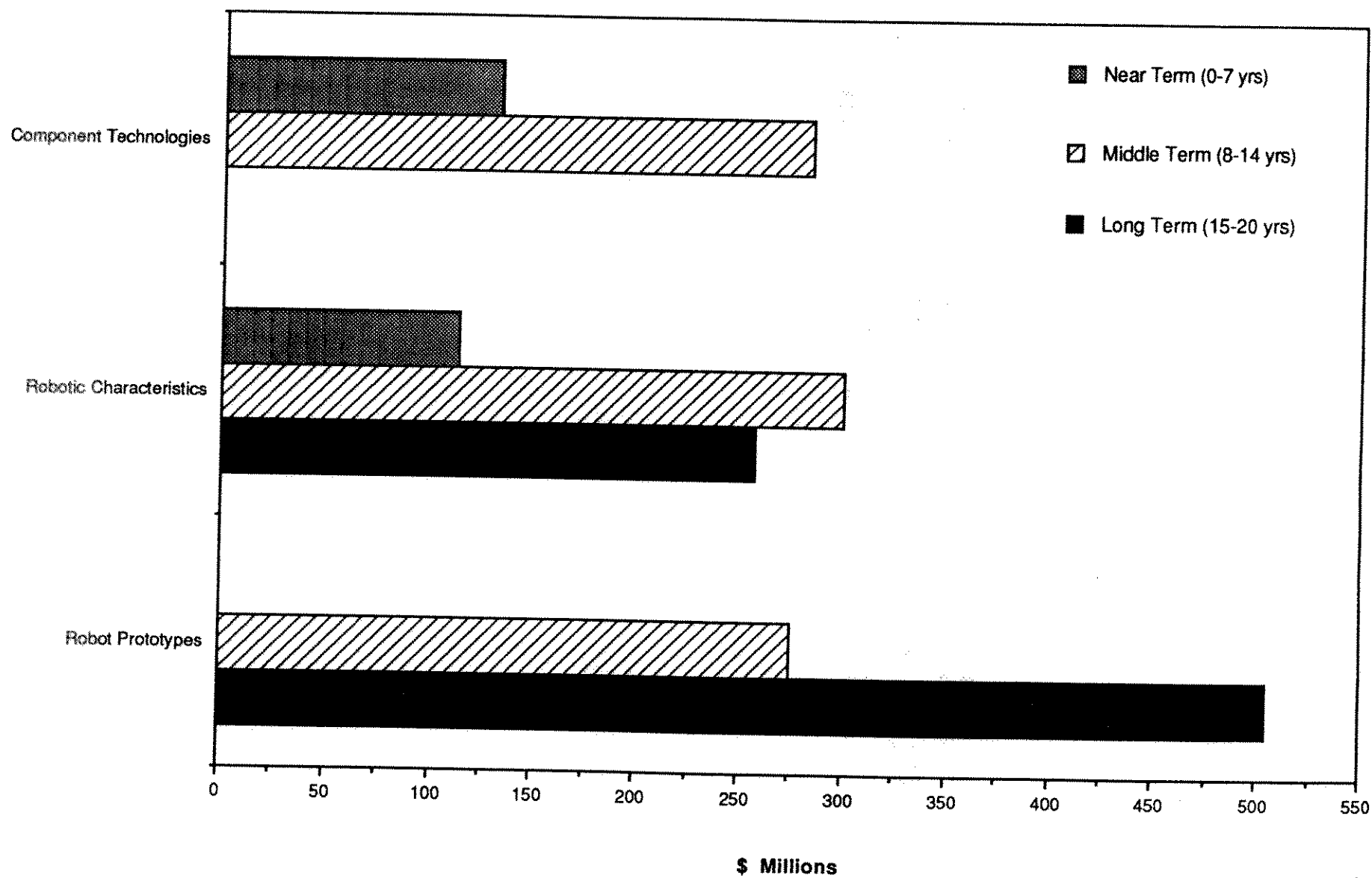


Chart 10. Overall Plan to Establish Robotic Systems for Space Operations



**IMMEDIATE RESEARCH NEEDS
FOR SPACE ROBOTICS FOR THE
LUNAR AND MARS MISSIONS
(INCOMPLETE)**

IMMEDIATE RESEARCH NEEDS FOR SPACE ROBOTICS

- ARCHITECTURE OF ROBOTICS SYSTEMS
- UNIVERSAL MAN-MACHINE INTERFACE FOR ROBOTIC MANIPULATOR SYSTEMS
- CONTROL OF MULTIPLE ARM ROBOTIC SYSTEMS
- ROBUST CONTROL OF FLEXIBLE "CHERRY PICKER" ROBOTIC MANIPULATOR
- REALTIME SYSTEM MODELING FOR MODEL REFERENCE ADAPTIVE CONTROL
- METROLOGY FOR ROBOTIC SYSTEMS
- COMPUTER ARCHITECTURE/COMPUTATIONAL SOFTWARE
- VISION (ANALYSIS AND ENHANCEMENT)
- DATA BASE AND ARCHIVING
- KNOWLEDGE BASES
- COMMUNICATIONS TECHNOLOGY

A Fully Reconfigurable Modular Robotic Architecture

- **Modular Robots** - high strength-to-weight ratio composite links, reconfigurable for varying workspace, force, position, degree-of-freedom, and load-carrying requirements.
- **Manual Controller/Man-Machine Interface Technology** - for universal teleoperation and supervisory control of a broad range of reconfigurable robots.
- **Advanced Sensor Technology** - vision, force feedback, control feedback, environmental sensors, etc.
- **Modular Controller Systems**
- **Artificial Intelligence** (decision-making software)
- **Advanced Training and Performance Enhancement Software**

Advantages of Modular Reconfigurable Robotic Architecture in Space Robotics

Modularity in: Actuators
Undriven Joints and Links
Structural Modules
Control Systems
Software
Sensors

- Standardized modules and interfaces allow upgrading of equipment (techmods) as technology improves, reducing major operational disruptions and the threat of obsolescence.
- Easily replaced modular components make repair/replacement easier, less costly.
- Reduced parts inventory saves space and weight, reducing launch costs.
- Allows configuration and assembly of specialized systems in space.
- Decreases design cycle time.
- Optimized design process improves reliability, decreases design costs.
- Precision is improved due to aggressive design optimization in the modules.
- Allows different systems to be cross-compatible.

MODULAR MANIPULATOR **ARCHITECTURE**

1. SYSTEM COMPOSED OF GENERIC MODULES

- Easily Scaled to Size of Task
- Easily Interfaced Because of Standardization
- Rapid Changeover for Enhanced Tech-Mod's
- Rapid Diffusion of Technology
- Reduced Level of Design Effort
- Reduced Threat of Obsolescence

2. SEVERAL UNIQUE MODULES

- 3 DOF Shoulder
- 3 DOF Wrist
- 2 DOF Knuckle
- 1 DOF Elbow
- 6 DOF Micromanipulator

3. FLEXIBILITY FOR SYSTEM COMPOSITION

- Up to 12 DOF
- Exceptional Dexterity
- Excellent Obstacle Avoidance
- Reasonable Structural Integrity

4. INTEGRATE THE BEST COMPONENT TECHNOLOGIES

- Parametric Modeling
- Adaptive Control
- Decision Making
- Manual Intervention
- etc.....

5. MEET THE MOST DEMANDING SYSTEM REQUIREMENTS

- High Operating Forces
- Cluttered Obstacles in Work Environment
- Numerous Distinct Tasks
- Precision Machining
- etc.....

UNIVERSAL MAN-MACHINE INTERFACE FOR ROBOTIC MANIPULATOR SYSTEMS

OBJECTIVE

- A TRANSPARENT, UNIVERSAL INTERFACE BETWEEN OPERATOR AND ROBOT

JUSTIFICATION

- LEVEL OF MACHINE INTELLIGENCE FOR COMPLEX TASKS NOT AVAILABLE FOR TWO DECADES
- BEST NEAR-TERM SOLUTION: PROVIDE HUMAN INTELLIGENCE FOR SEMI-AUTONOMOUS MACHINE OPERATIONS

CONTROL OF MULTIPLE ARM ROBOTIC SYSTEMS

PROPOSED RESEARCH

- **DEVELOPMENT OF CONTROL TECHNOLOGY TO
COORDINATE REQUIRED FORCE-MOTION
INTERACTIONS**
 - **KINEMATICALLY DEPENDENT ACTUATOR
MOTIONS**
 - **BALANCE ACTUATOR LOADS:**
 - **CREATE DESIRED RELATIVE FORCES**
 - **PREVENT ACTUATOR OVERLOADS**
 - **PREVENT LARGE DEFORMATIONS IN THE
MANIPULATOR**
 - **PRECISION UNDER DISTURBANCE**
 - **REAL TIME BALANCING OF ABOVE**
- **ESTABLISH CRITERIA FOR MULTIPLE ARM
OPERATION AND DESIGN**
- **DEMONSTRATE SPECIFIC SATELLITE
MAINTENANCE TASKS**

REAL-TIME SYSTEM MODELING FOR MODEL REFERENCE ADAPTIVE CONTROL

NEEDED DEVELOPMENT

- **DEMONSTRATE MODEL REFERENCE CONTROL**
 - **RIGID LINK MODEL**
 - **COMPENSATE FOR APPLIED LOADS**
 - **COMPENSATE FOR INERTIA LOADS**
- **EXPAND TO INCLUDE DEFLECTIONS**
 - **LINK FLEXIBILITY**
 - **ACTUATOR FLEXIBILITY**
- **ESTABLISH OPERATIONAL SOFTWARE**
- **DEMONSTRATE IN ACTUAL MACHINING OPERATIONS**

TASK DESCRIPTION

- **EXPAND RANGE OF APPLICATIONS**
 - **FOR GENERIC MANUFACTURING SYSTEMS**
 - **USE FEED FORWARD COMPENSATION**
- **ON LINE COMPUTATION**
 - **FULL MODELING MATRICES**
 - **REAL TIME (<30 MSEC.)**
- **ARRAY PROCESSOR IMPLEMENTATION**
 - **PIPELINED COMPUTATION**
 - **RECURSION IN ALGORITHM**

METROLOGY OF ROBOTIC SYSTEMS

OBJECTIVES

- **DEVELOP AUTOMATED TECHNIQUES FOR DETERMINING ROBOT PHYSICAL PARAMETERS "AS BUILT"**
 - **GEOMETRIC DIMENSIONS**
 - **MASS DISTRIBUTION**
 - **FLEXIBILITY PARAMETERS**
 - **ACTUATOR CONTROL PARAMETERS**
- **AID DEVELOPMENT OF ROBOT STANDARDS**
- **CHARACTERIZE EXISTING ROBOTS**

JUSTIFICATION

- **ROBOTS ARE NOT "ACCURATE"**
- **CLAIM ONLY REPEATABILITY**
- **METROLOGY IS BASIS TO IMPROVE ACCURACY**
- **LACK OF ACCURACY IS MAJOR IMPEDIMENT**
 - **TO OFF-LINE PROGRAMMING**
 - **TO FULLY AUTOMATED FACTORY**

APPENDICES:

Comments by Consortium Principals

**HUMAN PERFORMANCE
AND
HUMAN ENGINEERING ISSUES
NASA LUNAR/MARS MISSIONS**

**G. Kondraske, UT Arlington
September 11, 1989**

There is a need to focus on the following items:

- Determination of representative and worst case tasks and task requirements. Task requirements should be developed in terms of: (1) function, (2) quantitative high-level task performance (e.g., masses, distances, object dimensions, execution speeds, accuracies, etc.) and (3) quantitative estimates of the amount of stress placed on specific human performance resources (e.g., strength of specific muscle groups, ranges of motion, movement speeds, visual information processing speed, etc.).
- Simulation tools which can be presented within the workstation (e.g., for the control of robotic systems or vehicles) or other physical task scenarios (from a library of those anticipated to be necessary) and which provide: (1) predictions of failure/success at a desired level of task performance based on the stresses imposed on human performance resources, (2) quantitative estimates of margins of safety (based on resource reserves), (3) the ability to facilitate experimentation with alternate mission scenario designs and estimate relative workloads imposed by each.
- Quantitative model of muscular, cardiovascular, and mental fatigue. Such models should be able to receive temporal task assignments and estimate whether the imposed load causes endurance thresholds to be exceeded. Special attention: (1) Mental endurance associated with telerobotic operation with specific systems. Integrative (whole body) systems models for muscular fatigue (e.g., as for long duration EVAs, etc.). Models should include simple simulations of environmental effects.
- Methodology and simulations/experimental studies to permit analysis of humans and robots working together or sharing task components within a larger objective. Trade-offs (human vs. robot) and optimal resource utilization should be emphasized.

DESCRIPTION OF SPACE MANIPULATOR SYSTEM REQUIREMENT

D. Tesar
THE UNIVERSITY OF TEXAS AT AUSTIN
September 13, 1989

The complexity and range of physical tasks associated with space operations and exploration is enormous. See attached reference:

"An Assessment of the Development and Application Potential
For Robots to Support Space Station Operations"

These tasks involve assembly of space structures (handling of large modules, precise sub-assembly, precision welding and forming, etc.), space structure maintenance and repair (40% expected to be unplanned repairs, debris damage causes unstructured tasks containing disturbances, constant surveillance of space structures, etc.), moon surface resource retrieval (building and maintenance of human habitats, mining systems, hydrogen and oxygen plants, etc.), and Mars exploration (remote operation of surface vehicles, repair of facility damage, assembly of space telescope structures, etc.). Some of the complex dynamic motion tasks associated with these physical tasks are:

- Docking and grappling maneuvers
- Reactionless operations
- Stabilization, rigidization
- Dual robot operations
- Catching and storing space debris, etc.

Finally, a very broad range of unit processes are associated with these physical tasks:

Operation of simple mechanisms

latches, cranks, slides, handles

Joining and fastening

fitting, forcefit connectors, spot welding, forming, bolting
screwing, locking, coiling, riveting, electron beam welding

Precision Machining

grinding, sanding, brushing, drilling, routing, trimming, cutting

Handling

parts transfer, limp materials, fluids transfer, slippery materials,
warehousing

Automated inspection

seam tracking, surface flaws, meteorite damage on solar arrays,
thermal radiators, windows, mirrors, etc.

This spectrum of physical tasks suggests that a broad spectrum of robot systems will be necessary. The following is an abbreviated listing of these systems:

SYSTEM	DESCRIPTION	RANKING
1. Dual Arm ROV Module	Free-flying supply and maintenance system for unstructured tasks	10
2. Cherry Picker	Large (60 ft) and medium (60 in) robots in series	7
3. Medium Space Platform Robot	Workhorse robot (60 in) for precision operations	6
4. Large Space Platform Robot	Deployment robot (60 ft) for large motions	5
5. Spider Robot	Six-legged module for continuous inspection	3
6. Small Space Platform Robot	Small robot (15 in) for delicate assembly	2

This limited spectrum of required systems suggests a very demanding tech base development requirement:

1. Lightweight - This means that the robot's structures will be exceptionally limber and resulting deflections must be compensated by employing sophisticated parametric models in terms of a control technology far beyond that of the state-of-the-art.
2. Precision Under Disturbance - Many of the unit processes will involve force disturbances making precision operation difficult. This means that a real-time dynamic model using dedicated high speed hardware and software will be essential to achieve feedforward deflection compensation and adaptive control.
3. Enhanced Technology - Today's industrial robots (the 2nd generation) are far removed from the technology required for space (the 4th generation) based on a high level of modularity, generalized geometry (serial, parallel, layered, and redundant) and high speed computational HDW and SFW. It requires a full balance of the electrical and mechanical disciplines with an increasing role for computer science.

The principal requirement that must be met for future implementation of robotics in space is the ability to create a large spectrum of robot systems from a limited collection of hardware and software modules. This full modular architecture would allow a rapid reconfiguration of a given system, reduce the cost of transport, allow tech mods (technical modifications) for rapid infusion of new technology, and reduce the real threat of obsolescence. This general architectural requirement is the primary thrust of the present technology forecast.

MODULAR ARCHITECTURE MONOGRAPH

Michael S. Butler & Delbert Tesar

ABSTRACT

I. INTRODUCTION

II. EXISTING ROBOT TECHNOLOGY

III. MODULAR ARCHITECTURE FOR ROBOT STRUCTURES



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June 1989 issue
of
**Manufacturing
Review**

IV. COMPONENT TECHNOLOGY

V. CRITERIA FOR SUCCESS

VI. APPLICATIONS / CRITERIA MATRICES

VII. 30-YEAR FORECAST



Published in
Mar. 1989 issue
of
**Manufacturing
Review**

VIII. RECOMMENDED RESEARCH PROGRAM

IX. CONCLUSION

ACKNOWLEDGEMENTS

REFERENCES

SOME MACHINE VISION REQUIREMENTS FOR SPACE APPLICATIONS

R. de Figueiredo, Rice University
September 13, 1989

(1) MODELING

- Geometric and/or relational models for *targets*;
- Envelope models for *obstacles*;
- Generic (random field) models for *clutter*.

(2) SCENE DEFINITION

- *Illumination* strategies to enable and/or enhance image acquisition;
- Development of *high definition* sensors (e.g., HDTV, LIDAR devices);

(3) COOPERATIVE SENSOR OPERATION

- Intelligent real-time cooperation between camera and LIDAR

(4) RECOGNITION

- *Image segmentation* schemes to localize objects on image;
- *Detection* of objects on image as being targets, obstacles, or clutter (isolated or overlapping);
- *Classification* of a given target according to its category;
- *Estimation* of feature (shape) parameters of targets;
- *Learning* to classify new targets without supervision (e.g., by cluster analysis);

(5) LOCALIZATION OF TARGETS AND OBSTACLES

- Determination of position and orientation of given target as well as distance from an obstacle both in static and dynamic environments;

(6) TRACKING OF TARGETS AND/OR OBSTACLES

- Based on predictive models

(7) SAME AS (4), (5) AND (6) FOR THE MULTIPLE TARGET / MULTIPLE-OBSTACLE CASE

(8) IMAGE UNDERSTANDING OF RESULTS IN (7) DRIVEN BY A KNOWLEDGE BASE

- Sensor-assisted *navigation, grasping, assembly, disassembly, etc.*

Estimates of Parametric Requirements for Space Operations

Parametric Requirements

Function	Gravi- tational Environ- ment	Inspection Capability	Mass Movement Capacity	Reach / Range Capability	Dexterity Capability	Special Skills	Tele- operation Distance	Duration of Function- ality	Earth Weight	Power Require- ments	Readiness
Assembly of Structures and Repair	1/6-1/3 g	tactile, force, moment	1 - 50#	2 - 5'	high	auto- nomous fine motion	1 - 240K mi.	1 - 8 hrs at a time	100 - 500#	5 - 20 KW	5 - 10 yrs.
Inspection of Structure	0 - 1/6 g	intensity range vision	1 - 2#	3 - 10'	low		1 - 200M mi.	2 - 8 hrs	50 - 300#	1 - 5 KW	5 - 10 yrs.
Inspection of Plant Growth	1/6 - 1/3 g	intensity image vision	1 - 2#	3 - 10'	low	texture and color recognition	1 - 200M mi.	2 - 8 hrs/session	50 - 300#	1 - 3 KW	5 - 10 yrs.
Tending of Plant Growth Cells	0 - 1/3 g	visual, texture, tactile, form	.1 - 5#	3 - 10'	high	handle floppy material	1 - 240K mi.	1 - 8 hrs at a time	50 - 300#	1 - 5 KW	5 - 15 yrs.
Mining	1/3 - 1/6 g	force, moment, visual	10 - 100#	5 - 10'	low	drilling, tool handling, many tasks	1 - 240K mi.	2 - 8 hrs at a time	300 - 1000#	5 - 20 KW	5 - 10 yrs.
Drill for Ore Samples	1/6 - 1/3 g	visual, chemical sensors	1 - 20#	~5'	low	drilling, chemical analysis	240K - 200M mi.	2 - 8 hrs	50 - 300#	1 - 5 KW	near-term
Pick Up Rocks	1/6 - 1/3 g	visual	1 - 20#	2 - 6'	low - medium	none	240K - 200M mi.	2 - 8 hrs	50 - 300#	1 - 5 KW	near-term
Scoop Soil Samples	1/6 - 1/3 g	visual feedback	1#	.5 - 3'	low		240K - 200M mi.	2 - 8 hrs/ mission	20 - 200#	1 - 5 KW	near-term

Dick Volz, Texas A&M University, Sept. 12, 1989

A GENERALIZED MODULAR ARCHITECTURE FOR ROBOT STRUCTURES

NOVEMBER 28, 1989

DEL TESAR/ UNIVERSITY OF TEXAS

A Generalized Modular Architecture for Robot Structures

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The critical issue facing designers of advanced robot architectures is how to take advantage of advanced electronic technology (encoders, arithmetic chips, high speed processor boards, etc.) to produce generic and more versatile mechanical robot structures at lower costs. Today, almost all robots are designed one at a time at exceptionally high cost of resources and time. Frequently, this level of investment induces the designer to be conservative, leading him to use only proven technologies—hence, his system is not only costly but frequently obsolete and cannot easily be redesigned when new technology becomes available. The pressing need is to achieve an architecture which can rapidly evolve in the same fashion as is now feasible for personal computers. The goal of this paper is to show how a highly structured modular approach to robot architecture can achieve these desired results. The paper begins by reviewing a diverse range of existing robot technology in order to demonstrate architectural principles that are being employed or are in development. The second part of the paper shows how to build a generalized mechanical architecture out of 1, 2, and 3-DOF structural modules driven by a finite set (3) of compact, lightweight, stiff, and redundant actuator modules. This resulting architecture is easily scaled, assembled, and multilayered, which should dramatically lower costs and provide significantly improved performance without long design-to-market cycles and the implied threat of obsolescence.

INTRODUCTION

The modularity of personal computers is now an accepted and necessary reality of computer architecture. Those systems are layered with nearly standardized interfaces and control software. Such modularity in robotics has been pursued only in the most elementary sense. A true architecture, where local priorities, scaling issues, subsystem integration, and so on are all involved, has yet to be dealt with. Such modularity and architecture is essential for the growth of the mechanical technologies, especially if their costs are to become more competitive. This class of architecture allows a continuous evolution of the system while preventing obsolescence by making "tech mods" feasible at the modular level without disturbing the system.

Ultimately, the success of an aggressive technology for robotics will depend on our ability to design the system to

meet a broad range of operational requirements in terms of an excess of 100 or more available system parameters (for a 6-DOF serial arm, there would be 18 geometric, 42 mass, 36 deformation, and 18 actuator parameters). Facing all of these parameters simultaneously would far exceed the computational capabilities of the largest of foreseeable computers. Hence, a strategy for design must be developed to break the design process down into a series of layers upon which interactive intervention by the designer through simulation is possible. Computer system designers complain that they have an incomplete strategy for design. Considering the level of architecture, system definition, determinism, linearity, etc., which exists for computers, it is not difficult to comprehend the much more severe task faced by the designer of robots which is a far less developed technology.

Table 1 is a snapshot of what is implied by mechanical architecture. The basis for much of our high speed production machinery (textiles, packaging, food making, etc.) involves

the use of multiple 1-DOF machines such as cams and linkages all tied to a rigid crankshaft to ensure that their separate functions remain in time phased relationships without drift, even under heavy loads. Machines have been adjustable in the small ever since the mechanical governor was developed for the automatic control of the speed of steam engines. Today, this linear structure is the heart of functional control of modern production machinery, where precise output parameters must be maintained. The adjustable control input is usually mechanically small relative to the primary motion structure. If the secondary input is nonlinear and highly coupled to the primary structure, then a complex analysis is required to predict stability and the response of the combined system. Generalizing this further, suppose that both inputs are equal in scale, nonlinear and highly coupled relative to the output function of the system. This type of system can either be serial (the inputs are additive) or parallel (the inputs are distributed). The result is the first level of structure which mimics the character of operation of a robot. In biological systems many joints are able to provide compact actuation of several degrees of freedom (elbow-1, knuckle-2, ankle-3, wrist-3, shoulder-3, hip-3, etc.). The joints themselves are undriven. The muscles act in parallel to provide the desired motion. Similarly standardized modules can be created for mechanical systems driven either directly at the joint or in parallel.

Combining six inputs, either serially or in parallel, allows the mechanical structure to duplicate the motion of a human hand (end-effector). If it is serial, it possesses a high level of dexterity. If it is parallel, it can carry a high load. The biological system is usually thought of as a hybrid of these. Putting extra inputs attached to extra degrees of freedom (DOF) results in a system which has more inputs than outputs. These extra DOF allow for choices to be made (obstacle avoidance, enhanced stiffness, enhanced speed, etc.), that is, the basis for intelligence. Finally, the extra DOF may be small (say 1%) relative to the primary input. Many of the requirements for system operation deal with small scale parameters (deformation, precision, drift, etc.). Hence, the small scale inputs can be used to treat the small scale functional requirements while the large inputs maintain the global operation of the system. This separation allows dedicated control technology at each scale and potentially could be achieved with the secondary system based on linear geometric transformations (i.e., linear control theory then applies).

EXISTING ROBOT TECHNOLOGY

This section is intended to outline in pictorial form the existing mechanical structure of robot technology, from industrial robots (of high populations) through to those in the concept stage associated with future applications (such as in space).

1. *Unique Structures (Fig. 1).* Here some unusual devices are presented. The first is the 500-year-old concept of a robot to duplicate the 4-DOF motion of a bird's wing by Leonardo da Vinci [Fig. 1(a)]. This device [11] shows an unusual awareness of the coupling of the inputs through cables and of the fact that nonlinear transformations between the input and output were feasible. This is particularly striking since the concept of the most elementary nonlinear transformer (the 1-DOF 4-bar linkage) was not understood at all by his contemporaries. Here, he shows how to combine four coupled highly nonlinear inputs in a true manipulator.

The second device [Fig. 1(b)] is the concept proposed by

GE [3] called Hardiman (1968). It was intended to enable a man to pick up a 1500 lb load from the floor to a 6 ft height and to walk up a set of stairs. The system was completely built around the concept of force-feedback in a position-, velocity-, and force-sensitive servo system. This is a direct example of human augmentation. It appears that this concept should be revisited not only because the technology is more available to develop the system today, but also because the human could be shielded from a hazardous environment (say temperature, radiation, chemicals, etc.). Today's feasibility for telerobotics lessens the urgency to carry out this development.

One of the most frequently seen [13] manipulators is the articulated excavator or "back-hoe" [Fig. 1(c)]. This is usually a 4-DOF planar system with in-parallel hydraulic pistons to drive the joints. The final DOF is the scoop which usually needs a 200°–240° rotation. This is achieved by using an augmenting 4-bar in series with the piston to amplify the range of the feasible joint rotation (from 120° to 240°). The primary requirement of the system is that it be able to develop large output forces.

The level luffing crane shown in Fig. 1(d) is widely used for ship cargo handling in European ports [19]. It is based on a 4-bar straight line linkage which maintains the load at the same elevation as it moves to and from the ship. The design enables the primary actuators (cable drive and crank drive) to be at the base of the structure. This concept has been expanded to cranes which use complex geared five-bar linkages as a foundation mechanism structure. Geared five-bar linkages (or two-input parallel structures) have been extensively studied by kinematicians over the past four decades. Their advantage to robotics is that it makes it possible to use heavy direct drive motors at the base without the penalty of carrying the motors on the moving links (as in a true serial arm).

The next device is associated with human augmentation. The 5-DOF manipulator envelopes a partially incapacitated human arm allowing it to carry heavier loads and to maintain more precise motions. The input is by a sponge ball held in the teeth of the operator. Prof. Louis Torfason [23] indicated that the prototype could be built at low cost but the delicacy of the servos made its reliability in the hands of non-technologists less than what would be tolerable. Perhaps with the use of much lighter (and reliable) electric servo motors in the near future, this device could be made sufficiently reliable to satisfy the demanding requirements of the user.

The tendon-driven finger [24] shown in Fig. 1(f) has 4-DOF and is driven by 8 separate cables under tension from 8 pneumatic prime movers. The finger acts as a module to make a four-fingered hand with exceptional dexterity and capacity for object manipulation. Each DOF is driven by two cables to create antagonism and smooth high resolution motion. Clearly the tapes (tendons) are highly coupled through the multitude of joints and associated pulleys. Tension sensors enhance the quality of force control. The system is under intensive technical, software, and control development, and its present state of operation is quite satisfying. The issue of complexity of parts, reliability, weight, multiple actuators, etc., just to operate a hand, makes realistic implementation in field systems quite problematical. Nonetheless, should truly small actuators become available for direct joint integration, the lessons learned will prove invaluable.

2. *Industrial Systems.* The devices in Fig. 2 have been built to meet heavy duty requirements found in industry or in

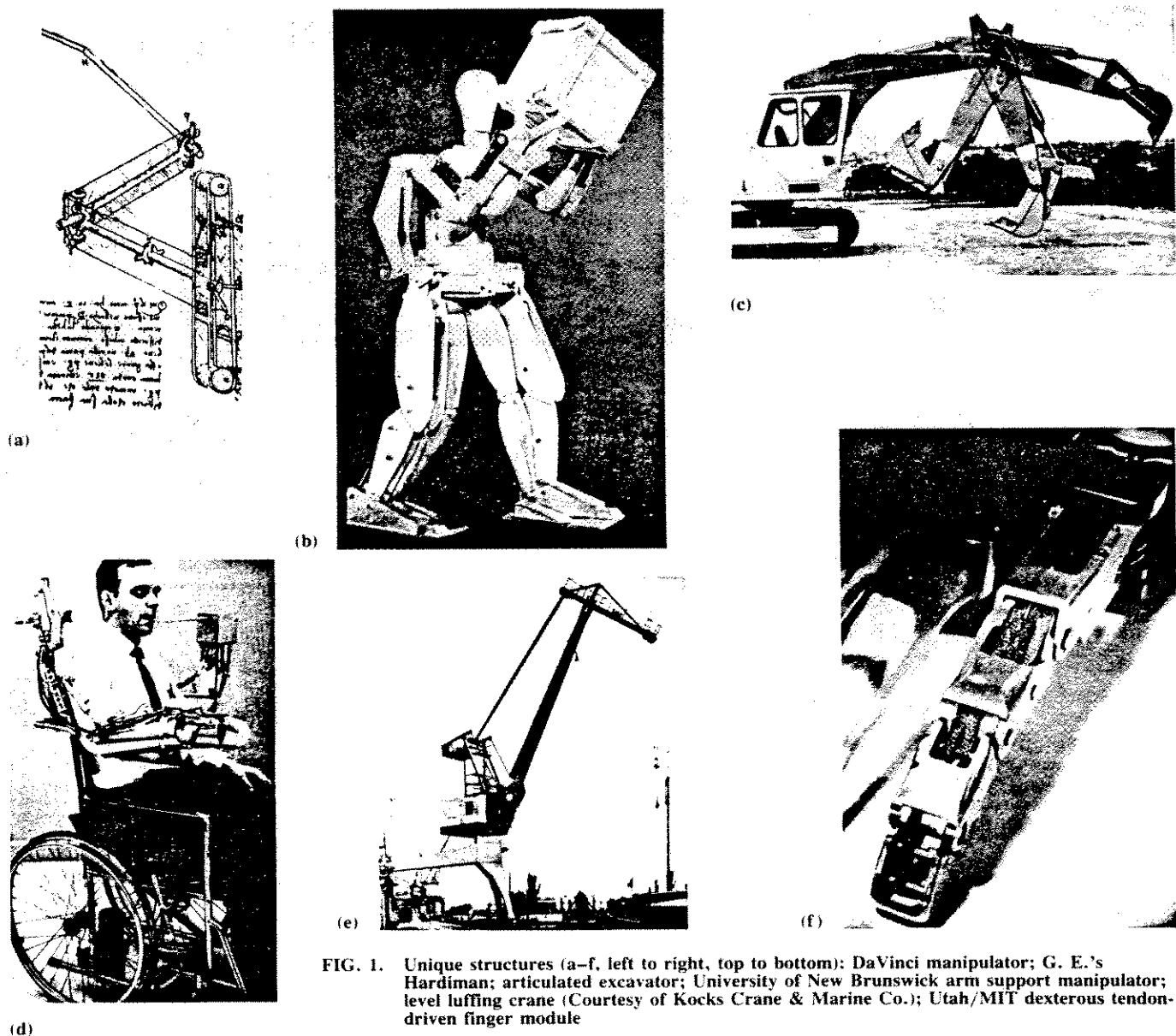


FIG. 1. Unique structures (a-f, left to right, top to bottom): DaVinci manipulator; G. E.'s Hardiman; articulated excavator; University of New Brunswick arm support manipulator; level luffing crane (Courtesy of Kocks Crane & Marine Co.); Utah/MIT dexterous tendon-driven finger module

remote hazardous environments. That in Fig. 2(a) represents a remarkably large device by GE called the Man-Mate [20]. It was intended to carry 3000 lb in a work volume of 11 by 17 ft and be controlled through a master-slave format by an operator in a protected cab. Many say that this device was ahead of its time and probably quite expensive. Nonetheless, it was an excellent effort to augment the human in the workplace.

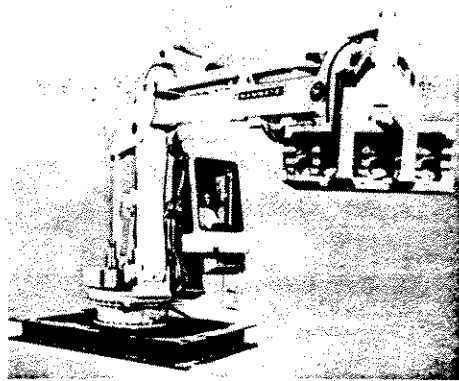
The DEMS (Driver Equivalent Manipulator System) [Fig. 2(b)] was also offered by GE for deep submersible work. It was operated remotely through a force-feedback master-slave [7]. Each of the first three joints was operated by a dual piston rack and pinion module. The system was very rugged but the small size of the pinion gear tended to magnify backlash problems. It was rated at 65 lb and had a reach of 5.5 ft and only weighed 320 lb.

Perhaps the most popular assembly robot in this decade [1] has been the Adept One [Fig. 2(c)] which is a Selective Compliance Articulated Robot Arm (SCARA) robot driven by

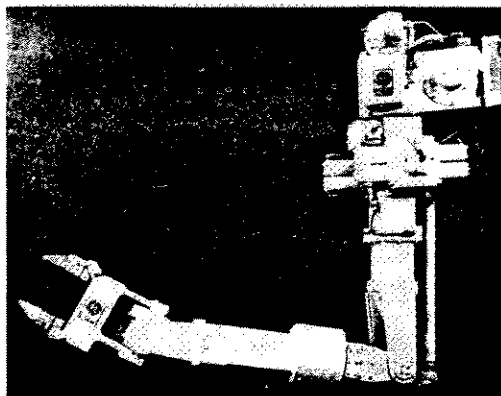
direct drive motors. The unit has a very small footprint, it looks clean, and it is smooth and reliable with good resolution. The vendor continues to develop software which enhances its programmability.

The robot [9] which appears to have the widest acceptance in heavy duty applications is the Cincinnati Milacron [Fig. 2(d)] electric T3 series (the 746, 776, 786, etc.). It exhibits a remarkable resolution of 0.01 in. in a large workspace. The 776 weighs 5500 lb. Even though it is well designed mechanically, it deforms 0.20 inch under its payload of 150 lb. This means that precision tasks are not feasible under computer control (off-line programming) if there is a significant force disturbance in the process being performed by the robot.

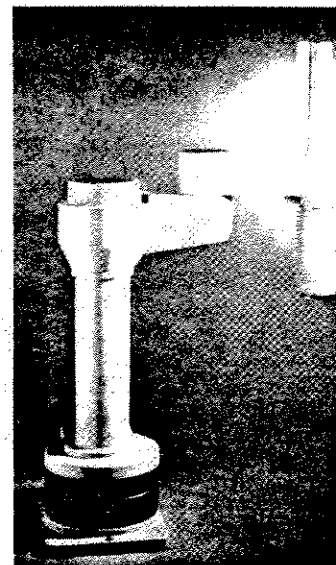
The gantry system [67] has become a recent standard configuration for industrial robots. It allows a 2-DOF platform to cover a large workspace with a 5- or 6-DOF manipulator without interfering with access to the work volume from all



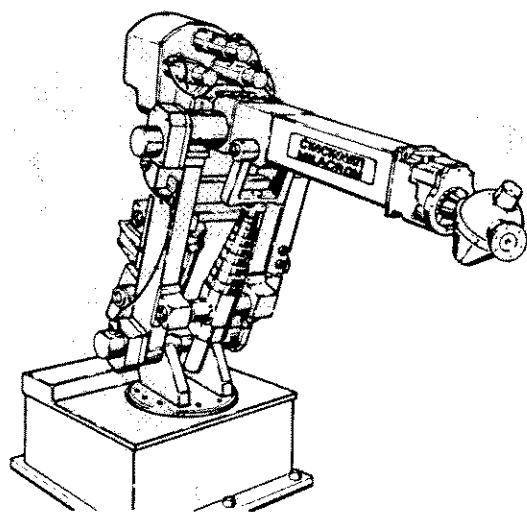
(a)



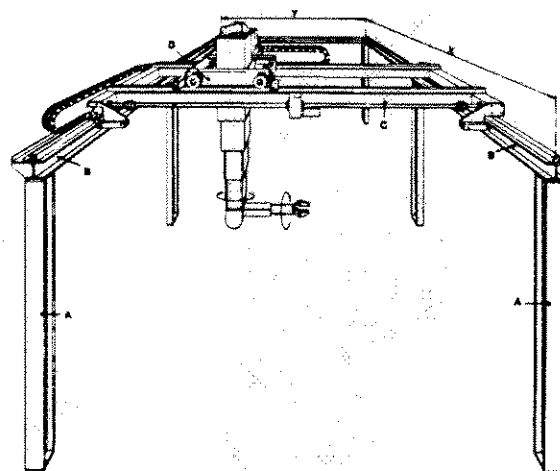
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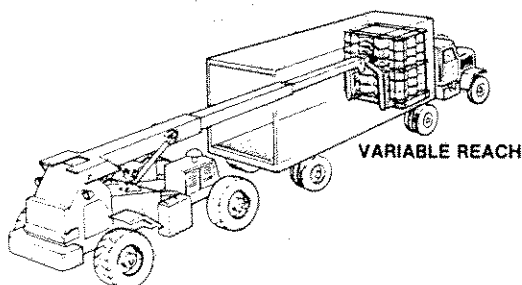
(c)



(d)



(e)



(f)

FIG. 2. Industrial systems (a-f, left to right, top to bottom): G.E.'s Man-Mate 2000; G.E.'s underwater manipulator; Adept one assembly robot; Cincinnati Milacron industrial robot (T3-776); gantry robot; field material handling manipulator

sides. These devices can be quite large. They are difficult to operate accurately over large volumes unless high quality laser sensors are used along the $x-y$ frame. Unfortunately, laser measurement of the end-effector location in space remains expensive. Robust (but expensive) gantry systems have been used to perform some light machining tasks, such as drilling of relatively flat panels found in aircraft [Fig. 2(e)].

The material handler [38] shown in Fig. 2(f) is representative of the concepts now being considered for use in the battlefield. It has rubber tires to allow it to convoy at 40-50 mph. It is to be operated from a standoff position and transport up to 10,000 lb loads. Considering the dilemmas of soft

tires, sloping or soft terrain, human error, and so on, the requirements for modeling and control are demanding. Even though this device at first appears to be quite simple, the level of flexibility (link and tire deformation), the high load capacity, and the danger that the operator could overcommit the handler suggests that this system can be extremely interesting to the technologist.

3. *Interesting Prototypes.* Some very interesting prototypes [Fig. 3] have been developed over the past two decades (some well known and others not). The Martin Marietta Proto-Flight Manipulator Arm [8] developed for MSFC by a team led by Bill Britton deserves special mention [Fig. 3(a)].

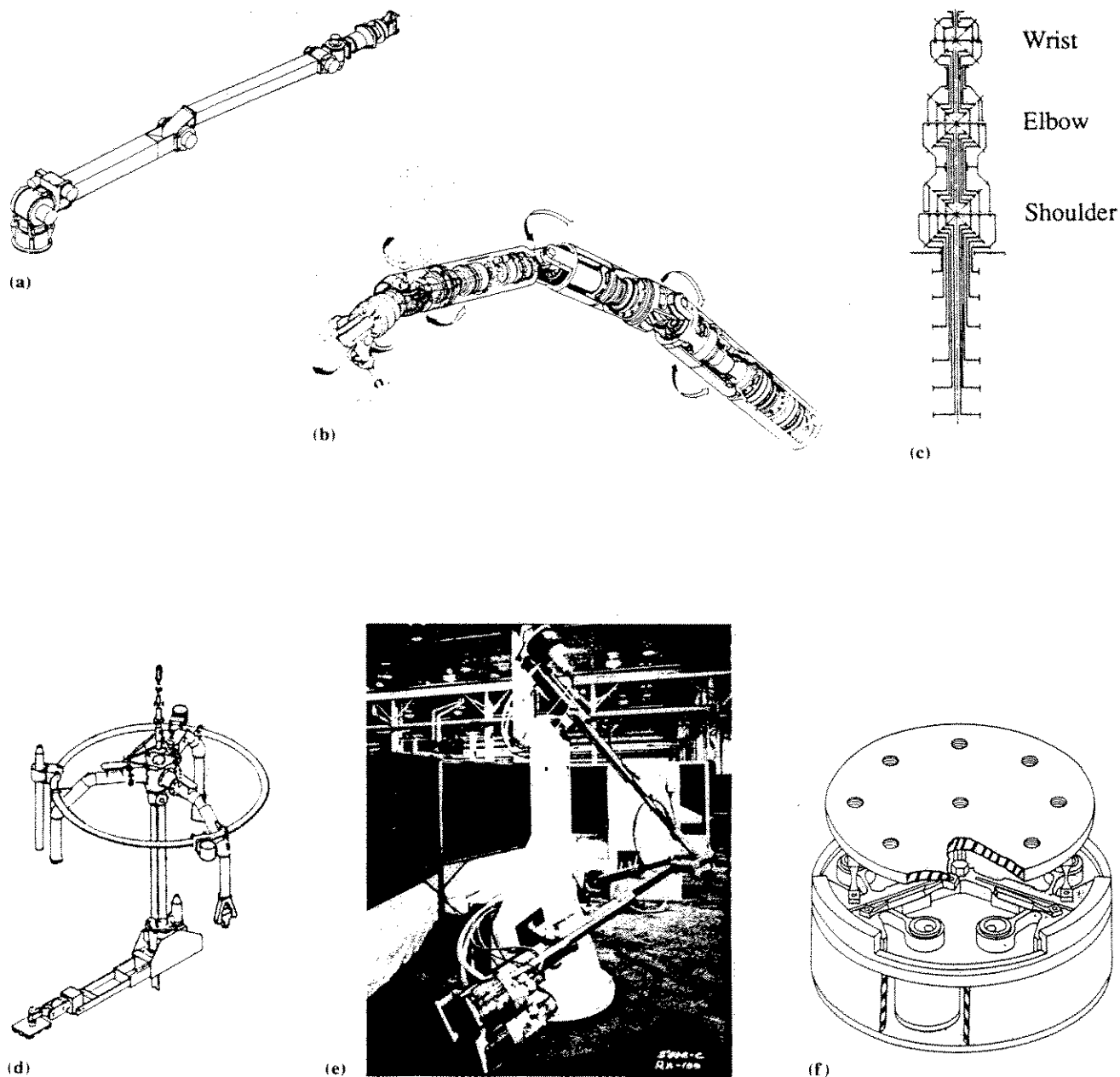


FIG. 3. Interesting prototypes (a-f, left to right, top to bottom): Martin Marietta's Proto-Flight Arm; Russian bevel gear drive manipulator; bevel gear-motor modules in manipulator arm; 11-DOF reactor vessel inspection robot by Westinghouse; Lamb Corp. prototype tripod robot; micromanipulator (based on Stewart platform)

It weighed 115 lb, could generate a force of between 11 and 15 lb, and could reach 8 ft. It was a 7-DOF system and could easily fold up for stowage. Several of its actuators used precision gears in an antagonistic drive for very high resolution [see Fig. 7(d)]. In fact, the arm could easily pass for a first level effort at modularity. It appears to be the model for the RMS system that was produced by Canada for the shuttle.

The arm concept shown in Fig. 3(b) is due to efforts in the Moscow Machine Sciences Institute led by Academician K. Frolov [6]. The objective was to have all the prime movers at the shoulder so that they could be protected from heavy radiation in a nuclear work environment. The diagram shows

that a series of bevel gear drives enables the actuators to drive the end-effector in a programmed motion. Of course, the drive trains will be heavy, will exhibit backlash, are highly coupled, and will exhibit large torsional deformations in the large number of torque tubes. Nonetheless, the design deserves special consideration when extremely difficult environmental conditions are experienced.

The Taylor Hitec arm shown in Fig. 3(c) attempts to reduce the number of torque tubes used in the Russian example by placing compact drive modules within the tubular shapes of the manipulator links and using bevel gears to drive perpendicular joints at the end of each link [28]. This is an inter-

esting modular concept but it is limited by the friction, deformation, and backlash problems associated with bevel gears. Its major attribute is that it is slender and can maneuver through restricted channels or pipes.

The inspection robot by Westinghouse is a 11-DOF system intended to perform in-service weld and surface inspections of nuclear reactor vessels [40]. The geometry of the device is specifically suited to a cylindrical vessel. The system could be operated by human input or it could be preprogrammed to track the surface of the vessel. Because of the high need for dexterity and motion in restricted volumes, the system is primarily serial (one link, one joint, one link, etc.).

The one-off prototype [Fig. 3(e)] by Lamb Corporation is not well known [27]. Its extremely interesting modular and parallel structure deserves special attention. Each of its three legs is supported in a trunion and is actuated through a linear screw and a torque tube attached to a ring holding three pivots. The ring is the end-effector of the system. Because it is a tripod, no difficult coupling occurs. Also, it should be relatively stiff and capable of resisting significant force disturbance. It was planned to perform precision light machining tasks.

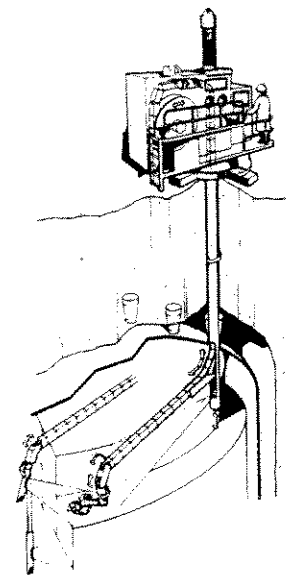
The micromanipulator device [50] in Fig. 3(f) is based on the Stewart platform having six identical modular legs. This device is intended to provide a vernier motion module at the end of the robot to provide high resolution or small motion feedback at the end-effector of a normal robot structure. The range of motion is ± 0.1 in. and $\pm 2^\circ$ of rotation in all 6 DOF. Each joint in the Stewart platform is provided by a flexible necked down section whose relative motion is restricted to prevent high stress levels. The device is intended to have a load capacity of 100 lb. Each leg is operated by a rare earth motor operating a compact harmonic drive (or similar purpose lightweight reducer) to reduce the size and weight of the motors. The overall weight of the module is intended to be approximately 20 lb.

4. *Snakelike Structures.* Several linear and multiply articulated robot structure prototypes which have a snakelike appearance have been created over the past decade. That shown in Fig. 4(a) is called the Spine robot [37, 41, 59] developed in Sweden. The goal was to create a system of unusual dexterity which would be able to reach into restricted spaces (i.e., pipes). The system was made up of a series of conical "vertebrae" driven by cables threaded through the edges of these elements. This system, however, is extremely deformable and can carry only light loads. It can only be programmed by using a master-slave or by extremely long iterative computations. It has not seen much use in the past few years.

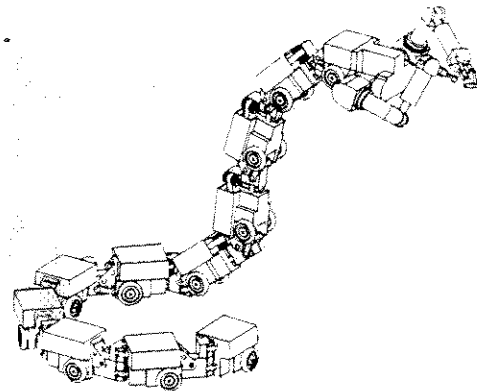
The device in Fig. 4(b) is an attempt to create a high level of accessibility for robotic devices which must travel through pipes to get to the work volume [28]. This is achieved by a "chain link" of box sections which has all joints in the chain parallel (a series of parallel revolutes). When the chain straightens out, the links mechanically "lock" to produce a light and relatively stiff structure. This system is highly modular and works only in one direction (i.e., it locks in only one way). The intention is to use this chain system to deploy the precision robot manipulator of Fig. 3(c). As shown in the figure, a mechanical assist (such as a shoe) must be deployed at the end of the pipe to guide the chain link to reach into the work volume in the desired direction. The shoe can be rotated remotely to improve access to the total volume.



(a)



(b)



(c)

FIG. 4. Snakelike structures (a-c, left to right): spine robot; waste cleanup manipulator; Odetics articulated (snake) robot concept

Table 1. Spectrum of Mechanical Structure

1. 1-DOF machines	cams, linkages, etc.
2. 2-DOF linear control structures	throughput gain by 2nd linear adjustment
3. 2-DOF machines adjusted in the small	throughput gain by 2nd coupled nonlinear small adjustment
4. 2-DOF machines	both inputs equally important and coupled
5. 1-3-DOF structural modules	elbows, knuckles, wrists, shoulders, etc.
6. 6-DOF robotic manipulator	duplicates human arm dexterity
7. 8-DOF robotic systems	allows obstacle avoidance and intelligent control
8. 12-DOF precision robot system	6-DOF large and 6-DOF small for precision under load

A recent and potentially very versatile transportation system to operate in a highly cluttered obstacle environment is the Odetics snake concept [60] shown in Fig. 4(c). This device is modular with 2-DOF joints between each module in the form of an actuated universal joint (two revolutes at 90°). The snake is intended to "jump" over relatively high obstacles against gravity. To do so would require 15 or more modules. At this time, prototype modules have been built and extensive control software development is underway. Its first mission objective is to work in hazardous radiation environments, to transport modules of a precision manipulator to the worksite, assist in its setup, and to provide tools and supplies to the work site.

5. *Walking Machines.* The concept of walking machines is very old and is found 200 years ago in examples called automata. During the 60s, DARPA contracted GE's Ralph Mosher [31] to produce a four-legged hydraulic walking machine [Fig. 5(a)]. Because of the lack of high speed computers, they were forced to have a master-slave arrangement where the front two legs were controlled by the operator's arms and the rear two legs were controlled by the operator's legs. The system was shown to work and Mosher could operate it over obstacles, but it was very taxing (because of the force feedback) and required considerable training.

In the early 80s, Odetics [4] developed a lightweight walking machine with six legs [Fig. 5(b)]. This system is modular in the sense that all legs are identical and symmetrically arranged on the "body." The leg has 3 DOF and is de-

signed to resist a heavy gravity load (a vertical force). Because it is symmetrical with six legs, it is very dexterous and can climb stairs and obstacles. It is technically capable of wall climbing in the format of a spider (by hand holds) but loses its load-carrying capacity because it is designed to resist a force in only one direction. By redesigning the leg, this weakness could be overcome although at a weight penalty. The climbing task would also require an exceptional effort in real time control software to balance all forces acting within the structure.

About 1980, DARPA again established a walking machine project with Professors McGhee and Waldron [41, 62] of Ohio State University. The resulting six-legged prototype is shown in Fig. 5(c). This device is intended to run at 8 mph and to carry a significant load (500 lb or more). The 3-DOF legs were carefully designed to resist gravity forces as well as significant lateral forces. Modified somewhat, it is capable of climbing (with hand holds). The principal problem of climbing will be the force balancing software which must be developed for all such highly parallel systems. In this case, there are a total of 18 input actuators which must be balanced in real time to create only six output forces (for load-carrying or for active force generation) if climbing and other generic force functions are to be achieved.

6. *Parallel Structures.* The walking machines in the previous section are all parallel in the sense that their active elements are distributed in similar articulated legs which act together to resist gravity. This section will deal with systems which are based directly on parallel mechanical structures. One of the first dexterous hands [Fig. 6(a)] was developed by Skinner [39, 46]. It is operated by only four motors and is capable of four distinct grasping modes. It can be made quite rugged, is mechanically relatively simple, and is relatively light. It can not, however, perform complex articulated motion of an object at its fingertips as is possible with the human hand.

The three-fingered articulated hand developed by Salisbury and Mason [35] is intended to be capable of dexterous object manipulation as well as grasping [Fig. 6(b)]. Each finger as a module has 3 DOF and is controlled by four cables. The total weight of the system is 14.5 lb. Each finger contains cable tension sensors in order to monitor the grasping force and therefore provide feedback to the rare earth drive motors. Fingertip peak forces are 10 lb. This system is being extensively analyzed kinematically to create force control software in order to make precise object manipulation possible. This class of balanced force-motion control in parallel systems is a problem of considerable interest to the research community at the present time.

A four-legged platform [21] for walking is shown in Fig. 6(c). This light-weight device has four identical modules having three inputs near the body which use pantograph amplifiers (3 to 1) to get the desired output range for the foot motion. Each pantograph is designed to structurally resist static forces without active force generation of the prime movers. The system is specifically designed to resist gravity forces; yet it shows an exceptional dexterity in its leg motion. The foot contains a sensor pad to measure contact pressure and cat whisker feelers to provide proximity awareness of obstacles. The overall impression is of an attractive balance of the required technologies.

Probably one of the earliest papers dealing with parallel structures was given by Stewart [44] in 1965. It deals with

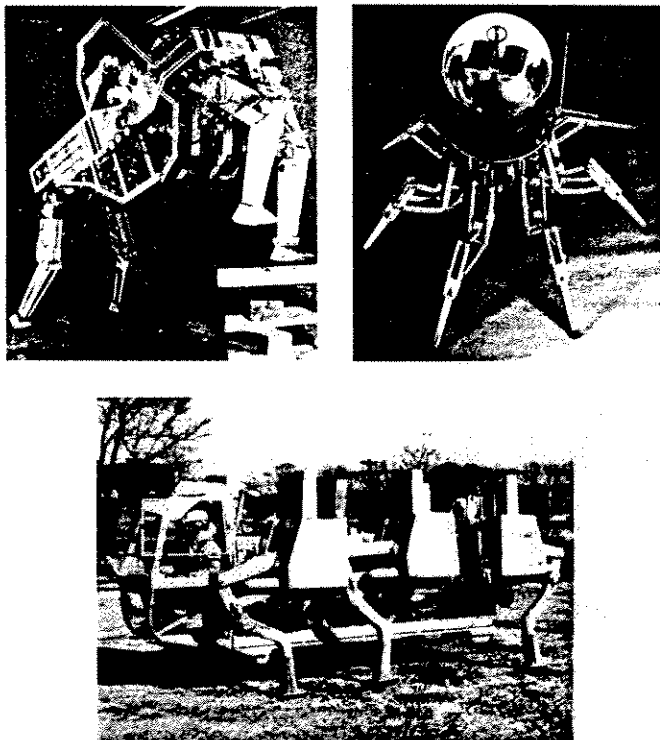
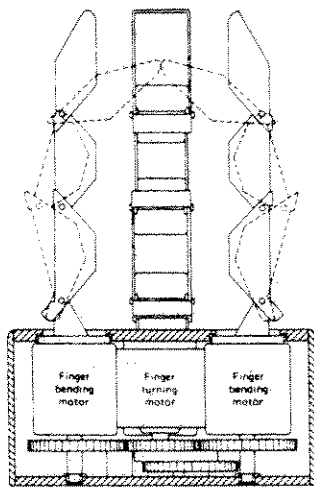
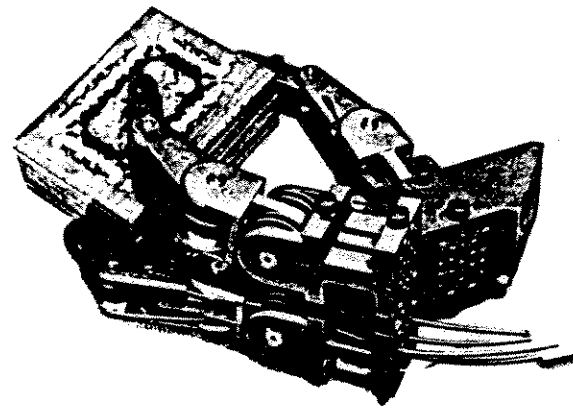


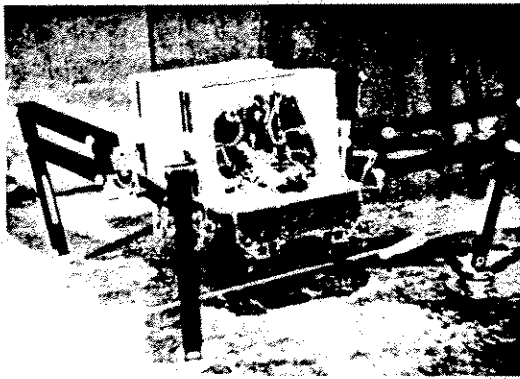
FIG. 5. Walking machines (a-c, left to right): G.E. quadruped walking machine prototype; Odetics six-legged walking machine; Ohio State University adaptive suspension vehicle



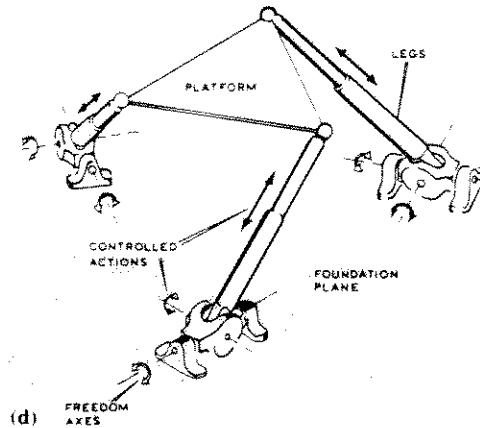
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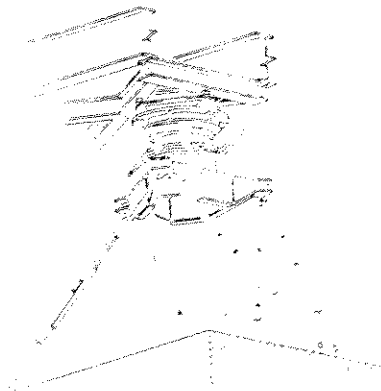
(b)



(c)



(d)



(e)



(f)

FIG. 6. Parallel structures (a-f, left to right, top to bottom): Modular three-fingered hand (Skinner); articulated three-fingered Salisbury hand; four-legged Japanese walking robot; Stewart platform concept; docking test mechanism (based on Stewart platform); link trainer (based on Stewart platform)

multilegged platforms to develop 6 DOF of programmable motion. The three-legged version is shown in Fig. 6(d). In his designs, each leg is an identical module and complete symmetry is maintained. Previous to the Stewart paper, a six-legged machine was used by V. E. Gough as a tire testing platform. A Mr. J. Tindale strongly recommended the Stewart

platform as the basis for a rugged dexterous precision machining system. Overall, all parties pointed out that parallelism and modularity would make the system economic, stiff, able to carry high loads, and be relatively light. It does carry the penalty of lower dexterity for its size, it tends to occupy much of its work volume, it requires a high level of force

control software to create a desired force output, and so on. Nonetheless, it is the simplest possible strictly parallel device. It can be operated by exceptionally simple kinematic analysis (position, velocity, and acceleration) software, and it can take on a large range of geometrical configurations at all scales.

The mechanism shown in Fig. 6(e) is a docking test system [45] based on a Stewart platform and operated in the mechanics laboratory at JSC. The platform is driven by six hydraulic cylinder actuators supported at each end by a 2-DOF universal joint (to make a 6-DOF modular leg). The initial use of the system was to test the docking mechanism to join the Apollo/Soyuz space ships. A complete dynamic model of the system has been simulated and demonstrated in the test module in terms of six load cells mounted on the support frame of the docking mechanism.

One of the earliest robotic systems is associated with the Link trainer [Fig. 6(f)]. This device [26] is intended to create motions to duplicate the dynamic phenomena experienced in flight by a pilot. The system is built with one hydraulic piston in each of six legs. The legs are all identical, having universal joint connectors at each end. The system is considered to be completely parallel since no two actuators provide forces or motions which add directly. The system could also be said to be highly modular since all the legs are identical. The need for very smooth motion at relatively high accelerations (and therefore high inertia forces) is best satisfied by this parallel structure. This smoothness can only be obtained by excellent coordinated motion and control. Many in the research community would do well to study the lessons learned in the operation of this system.

7. *Elementary Actuator Modules.* In order to design unique robot structures and to be able to create a full architecture for robotics, it is necessary to create building blocks of prime movers combined with mechanical structure to form structural modules [Fig. 7]. The most obvious source of inspiration is the biological system of articulated joints best understood in terms of the human structure. The human structure has been extensively studied by Morecki [32] and others. The forearm biceps are shown to be an "in-parallel" actuation of the elbow joint. This points out that few biological joints are operated by direct actuation at the joint. Most muscles operate only in tension (the equivalent of tensile cables), which is very efficient in weight and allows for a high level of antagonism, which is essential for high resolution work as occurs in painting, writing, throwing, and so on.

Of course, it is clear that Leonardo da Vinci understood a great deal about the mechanical structure of the human body. But his contemporaries barely understood the most elementary principles of machines. The need to develop a science of machines was pressing the community during the 18th and 19th centuries. A breakthrough occurred with the work of F. Reuleaux (1876), who showed how to unify the mechanical structure of machines using linkage chains [33] as basic to his presentations [Fig. 7(b)]. The device shown is a spherical 4-bar (which reduces to a planar 4-bar when the sphere has an infinite diameter). It is the most elementary nonlinear input-output device that exists. He showed how to generalize this to 6-bar, 8-bar, and 10-bar mechanisms. He also suggested a form of type synthesis to create a full architecture of machines. He demonstrated this type synthesis on a large collection of positive displacement pumps. During the 60s, Freudenstein [18], Woo [66], and many others showed how to perform numerical type synthesis of linkage systems. This

sophisticated technique (based on graph theory) was used to show that there were exactly 16 eight-link chains and 230 10-link chains, all kinematically distinct from each other. This class of graph theory might be useful for studying the full kinematic architecture of N -DOF systems.

The remote center compliance device [12] shown in Fig. 7(c) has become one of the best known add-on modules in the field of robotics. It possesses unique first-order geometric properties in a spherical geometry which extends its effective instant spherical center to a virtual location in front of the module. This extension makes it possible to passively accommodate assembly forces to prevent binding from amplification of contact forces. This requirement reduces the need for high positional accuracy in the assembly robot and can also enhance the speed of the overall process. Unfortunately, where precision operations must be maintained under force disturbances, the inherent softness of this module prevents accurate tracking as would be required in grinding, routing, drilling, etc.

The actuator module shown in Figure 7(d) was created by W. Britton at Martin Marietta [8]. He wished to eliminate backlash and therefore create a high resolution actuator. To achieve this, he divided the torque into two separate drive trains which are preloaded antagonistically by using antibacklash gears. The system does add some weight and increases friction somewhat, but it still provides very high resolution at low loads.

The actuator device shown in Figure 7(e) is a robust system of two hydraulic pistons driving parallel racks against one pinion [51]. The system is naturally antagonistic by balancing the low and high hydraulic pressures. Unfortunately, the pinion has to be small and it drives a small diameter shaft, both of which result in some backlash and low stiffness. In addition, the need to control large local gear forces and high hydraulic pressures results in an unusually heavy module for the level of torque output that can be achieved.

An older concept originated in the Argonne National Lab remote operations group is a cable driven wrist [10] which exhibits good dexterity and light weight [Fig. 7(f)]. It uses a differential bevel gear set to provide continuous rotation of the end-effector. Unfortunately, light bearings, close together, with small bevel gears result in high backlash and low stiffness. The system has proven useful in numerous designs but its inherent weaknesses prevent its further implementation in computer driven systems.

8. *Unique Robot Joint Modules.* Some particularly interesting robot joint devices exist as structural units that can be used as a basis for modular robots (Fig. 8). The first of these is the ingenious linear hydraulic actuator [Fig. 8(a)] developed in the 70s for the IBM gantry robot by P. Will [65]. This driver is a continuous sinusoidal cam built on a rack which is driven by a set of perpendicular hydraulic pistons which when activated cause linear motion to occur along the rack. This system exhibits inherent antagonism, eliminating backlash. Its main weaknesses appear to be leakage (unacceptable in a clean assembly environment), required distinct power source (heavy and noisy), and the fact that it is relatively heavy with respect to alternate drive modules.

Probably the earliest attempt to make a modular robot was by a team led by Don Adamski [29] at MB Associates (now a subsidiary of Tracor, Inc.) in the mid-70s. Westinghouse specified that no one part of a nuclear reactor maintenance robot weigh more than 35 lb so that it could be back-

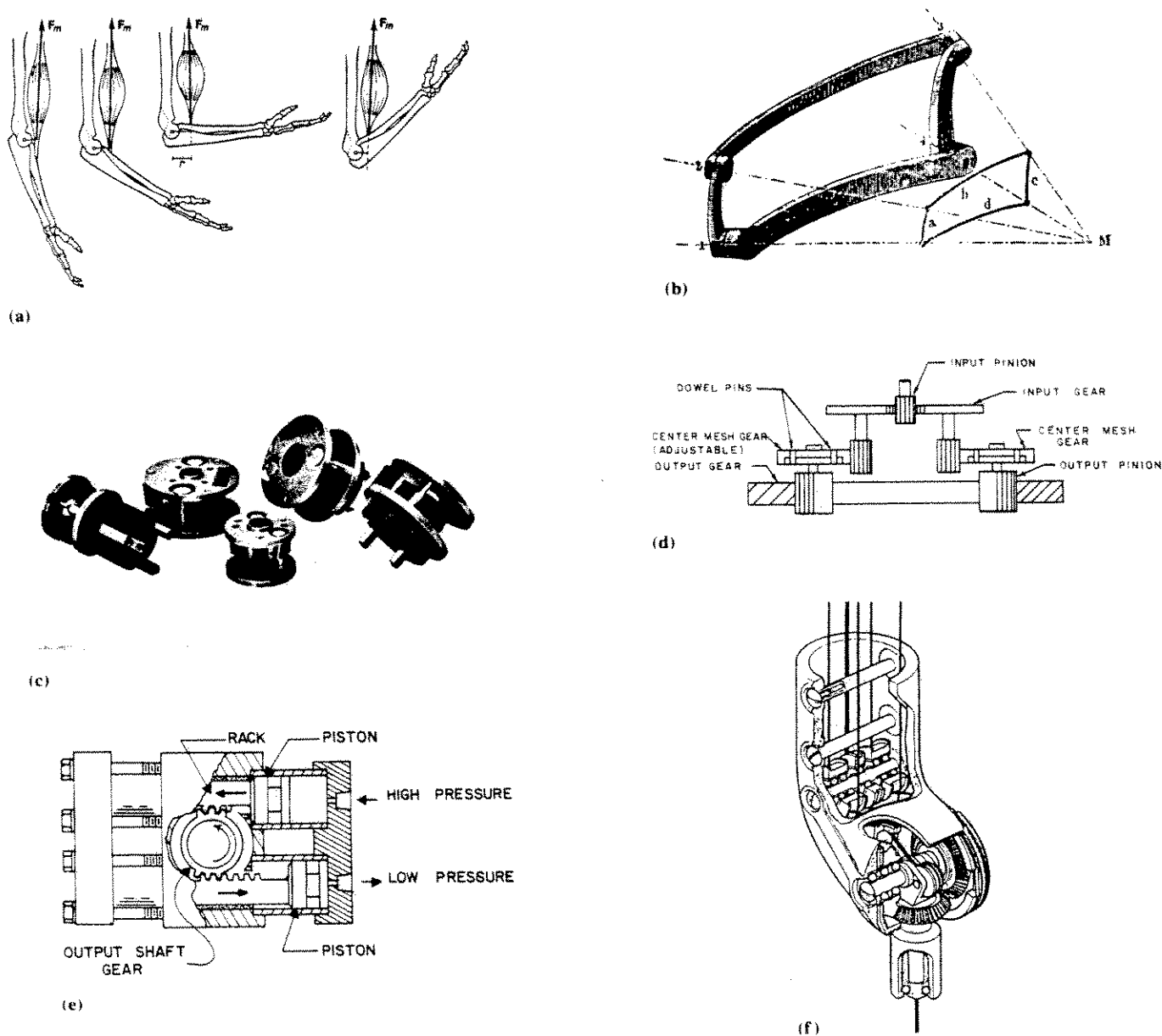


FIG. 7. Elementary modules (a-f, left to right, top to bottom): human arm showing in-parallel drive of elbow; fundamental spherical 4-bar concept by Reuleaux (1876); remote center compliance (RCC) module (Lord Corp.); Antibacklash drive gear train by Martin Marietta; opposed piston gear and rack actuator; early concept of a modular 3-DOF wrist by Goertz at ANL

packed by maintenance personnel. The resulting design of 6 DOF, including supporting frame, was estimated to weigh 280 lb. could be separated into eight modules, could carry a 60 lb load plus create a 180 lb bracing force, and exhibited an effective stiffness of 1500 lb/in. at the end-effector on a 60-in. long arm. The system was to be driven by specially designed lightweight single and double vane rotary hydraulic actuators using 2000 psi pressure. The breakdown module [Fig. 8(b)] was a precision-fit quick-disconnect unit (estimated to weigh 6 lb) which could be assembled by a single turn of a threaded connector collar. Up to 20 O-ring hydraulic face seals and 100 electrical line connectors could be supplied in the breakdown module. All indications are that this design

met the stringent requirements associated with entry through a 16-in. manway to perform tubing repair operations in the PWR steam generator.

Recently, much work has been invested [2] in developing a type of electric prime mover which can generate sufficient torque without the use of drive trains [Fig. 8(c)]. This unit provides exceptionally smooth motion with no backlash and little friction. A total robot system has been built using this as a driver concept. Unfortunately, in order to resist a reasonable force, these units become exceptionally heavy and large. They have been employed with success in SCARA robots where no gravity force acts directly on the joint prime mover. This type of device does not easily resist force disturbances and would

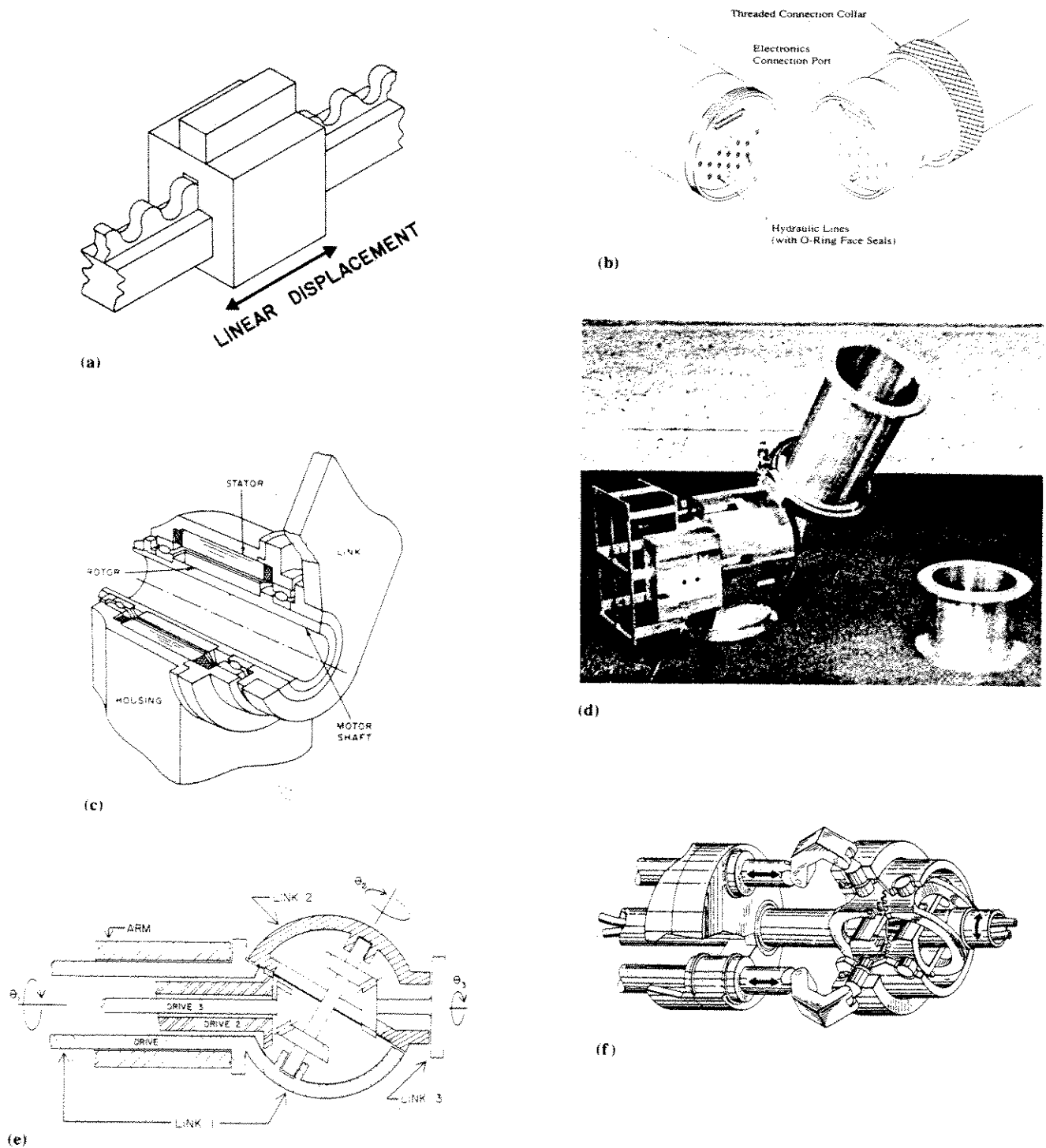


FIG. 8. Unique robot joint modules (a-f, left to right, top to bottom): linear hydraulic actuator concept by IBM (Will); hydraulic robot link modules (MB Assoc.); direct drive motor by Carnegie Mellon (Kanade); actuator module prototype by Carnegie Mellon (Kanade); Cincinnati Milacron's three-roll wrist; concept of wrist by Rosheim

therefore perform poorly where precision (under load disturbance) must be maintained.

The actuator module shown in Fig. 8(d) was recently suggested by Schmitz and Kanade as a basis for a modular

arm [36]. Each module offers the option of a link extension along the joint axis or perpendicular to it. A quick disconnect mechanical bayonet lock has been built into the module to allow quick joint replacement. Of course, a similar effort for

quick disconnect must be made for the control, current, data, etc. on umbilical. The concept, at first glance, appears to be too restrictive in the sense that no geometrical parameters exist in the joint to allow a general design to occur. In his paper, Kanade presents a very attractive argument in favor of modular robots.

Perhaps one of the most successful modules implemented in an industrial robot [43] is the three-roll wrist of Cincinnati Milacron [Fig. 8(e)]. The diagram shows a series of bevel gears which are sequentially driven by torque tubes in the forearm of the robot. This allows all the actuators to be placed behind the elbow [see Fig. 2(d)] and to make the forearm much lighter. Of course, the additive error in the serial bevel gears does result in some backlash and the long torque tubes are very soft under load. Nonetheless, the wrist's attributes are sufficient to overcome these problems. It is exceptionally compact and provides large motion ranges (very desirable in many automotive applications). It does exhibit the condition of control parameter singularity when the three axes of the wrist become colinear.

No discussion on modular robots can overlook the interesting wrist designs of Rosheim [34] shown in Fig. 8(f). These devices show complex means to drive the wrist rotations from remote prime movers. In many ways, the designs have a lot in common with automata. They do not exhibit a high regard for precision, load capacity, friction, number of parts, stiffness, and so on. As a basis for a general modular robot architecture, these limitations make their utilization unlikely. For special applications they may have merit. For example, for the low force application of spray painting, the 3-DOF wrist shown in the figure might prove entirely satisfactory.

9. University of Texas Structural Modules. The need for modules in robots derives from extensive experience in the development of remote maintenance systems for nuclear reactor maintenance (during the 70s). It was perceived that maintenance personnel would have to carry the robot in 35 lb units to the work site. This would require a high level of modularity and quick disconnect interfaces. The modules in Fig. 9 are partially due to this priority [47].

The first module shown in Fig. 9(a) is a secondary input to a large scale system [49]. It is essentially an eccentric driven through a worm gear by a small prime mover. It is scaled to be at 1% the scale of the primary inputs of the system. It enables the creation of a layered control that has been called "control-in-the-small." These small inputs can be distributed throughout the system (both in serial and parallel structures). Because much of the deformation under load in a robot occurs at very small scales, a feedback route to correct for this deformation can be taken through these small actuators (dedicated to this task) without disturbing the global motion and inertial control tasks of the primary actuator system. Also, should temperature, drift, and other "slow" effects occur at a lower scale, then another layer (say at 0.1%) of control could be implemented. This layering of control not only matches the scale of the associated physical phenomena, their related sensors, their control software, and so on, but they also could be linearized to allow the use of well established linear control techniques.

The concept of a 1-DOF elbow [47, 51] shown in Fig. 9(b) has been built and tested. It is a dual hydraulic system in antagonism driving a linkage amplifier to generate a rotation of 240° . This device was able to create a 5000 ft-lb torque using 1500 psi pressure on a 1-in. diameter piston. It exhibited

almost no backlash. The duality of inputs allows three modes of operation: push-push for high resolution, push-pull for high load, and push-preload to prevent backlash. The system is now being considered for use with a powerful pair of electric actuator modules.

The 2-DOF module in Fig. 9(c) is intended to be equivalent to a knuckle [47, 51]. It contains four actuator pistons to drive the two perpendicular joint axes in antagonism. Because of the isometric configuration, the system shows uniform stiffness in all directions. The duality of the hydraulic pistons means that all the modes of operation of the elbow are also available for this device.

The module shown in Figure 9(d) is intended for low force applications where precision is not a primary concern. It is essentially two half gimbals, combined with a central turning pair all locked together in a pair of cross-sliders. Each gimbal is driven at the base joint as is the vertical axis of the handgrip. The system can be made quite lightweight and appears suitable as the last 3 DOF of a modular manual controller [25].

The 3-DOF spherical shoulder [47, 51] shown in Fig. 9(e) has been under development for 10 years. All the joint center lines meet at the center of a sphere. The system is completely parallel in that three identical "legs" of two links each are used to drive the output plate (three rotations about the center of the sphere). The range of motion is approximately a 140° cone. Each lower joint can be powered by a rotary actuator. Since all the actuators are on the fixed link, their mass does not add to the inertia of the moving structure. Because of the complex geometry, there are a total of 54 independent component forces acting on the bearings and actuators of this module. But only 48 static equations are available to solve for all the unknown force components. Hence, compatibility equations based on link deformations must be used to develop six more conditions. This has been done in a recent report by Tesar and Craver [52]. A lightweight model of this shoulder is now being assembled. A robust shoulder is also being designed for evaluation as a heavy duty shoulder for an industrial robot.

The wrist concept in Fig. 9(f) has its origins in the shoulder [47, 51]. If you make all the base joints in the shoulder concentric, the result is a spherical wrist with a cone of motion of about 100° . It exhibits a high level singularity in the center of the sphere, suggesting that careful control over the input parameters would be necessary.

10. Modular Robot Concepts. Most modular robot systems are associated with tasks in space or in remote operations in the nuclear environment. Figure 10 shows six examples of modular robots, most of which are hybrid in the sense that the modules are placed in series in the structure (one module, one link, one module, etc.). As we have seen in walking machines and hand development, this hybrid serial chain is then used to form parallel structures such as the multi-arm devices in Figs. 10(d-f).

The hybrid miniature manipulator [58] in Fig. 10(a) is intended as a precision instrument to enhance the motor capacity of a surgeon by a factor of 10. The device is a series of 2-DOF universal joints specifically chosen so that preloaded jeweled bearings providing very low friction could be used. Because of the small scale, no actuator is small enough to drive the joints directly; hence, cable drives (three for each joint) are necessary to create an antagonistic control for high resolution—similar to the drives of the multi-cable hand shown in Fig. 1(f). A special miniaturized force sensor and

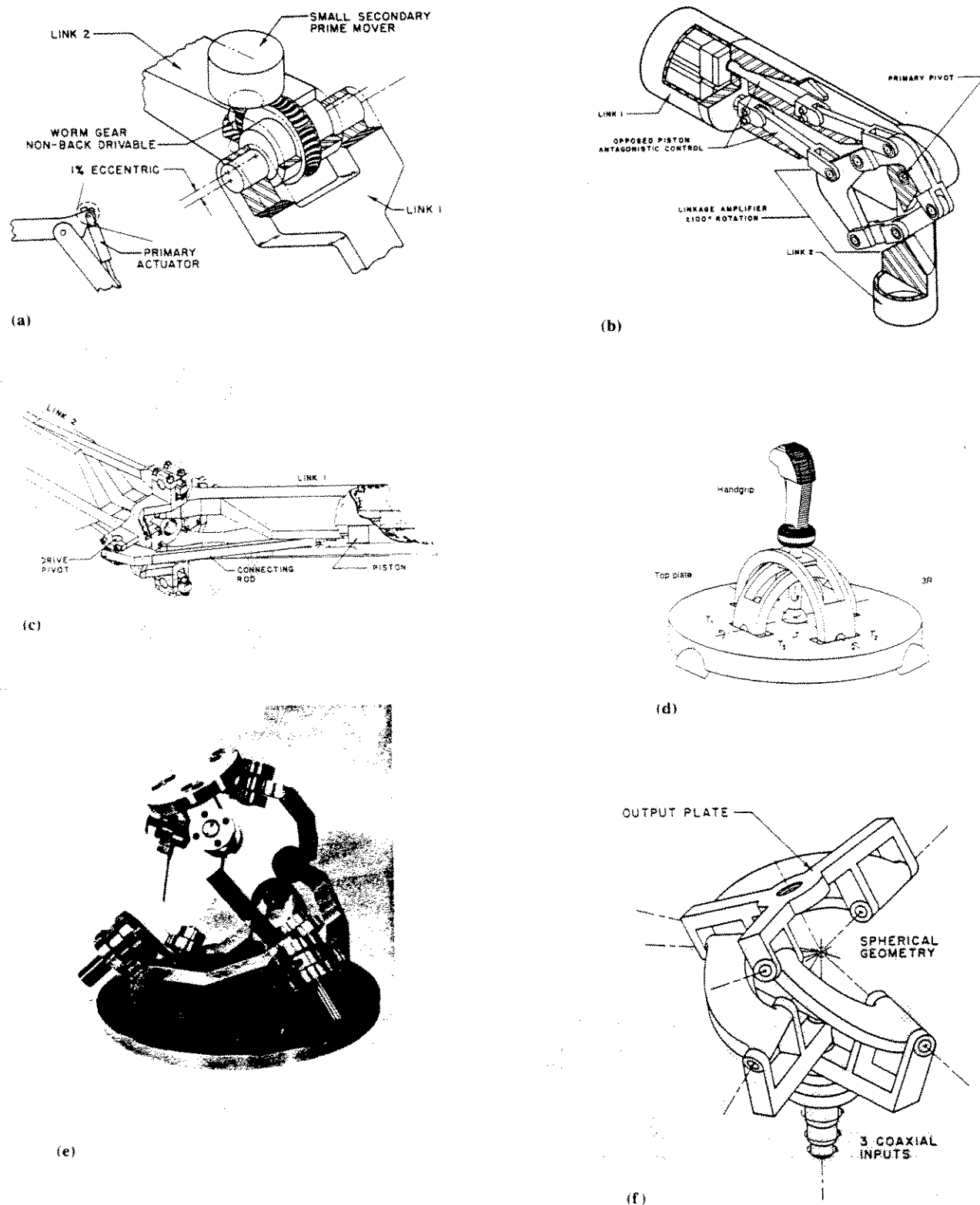
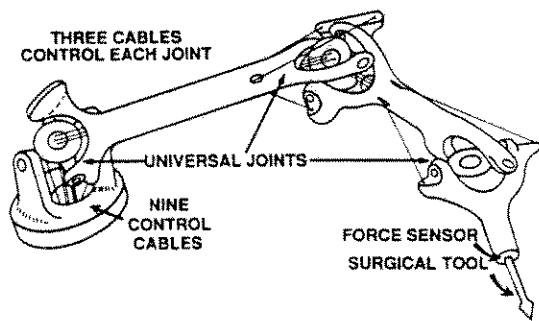
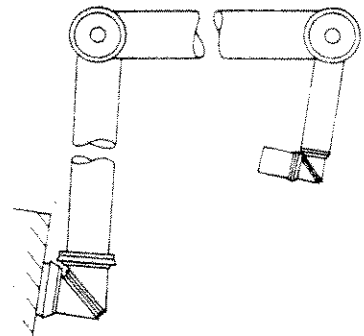


FIG. 9. University of Texas structural modules (a-f, left to right, top to bottom): eccentric drive for small motion inputs (Tesar); augmented elbow driven antagonistically (Tesar and Elliot); 2-DOF knuckle driven antagonistically (Tesar and Elliot); concept of partial gimbal for hand controller (Kim and Tesar); 3-DOF spherical shoulder concept (Tesar); 3-DOF spherical wrist concept (Hunt and Tesar)



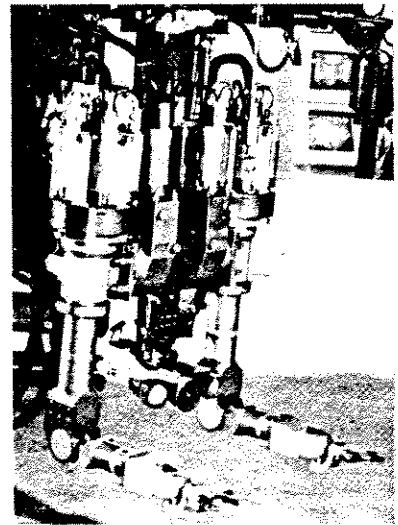
(a)



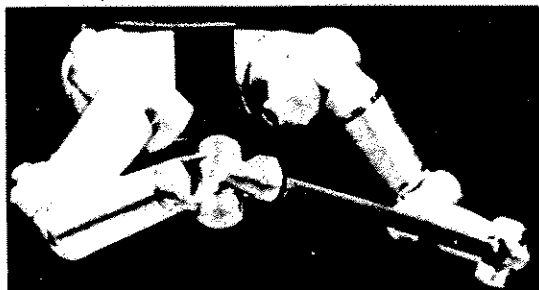
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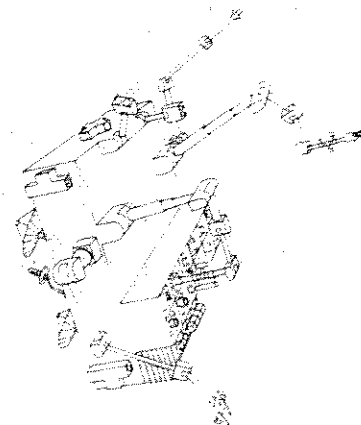
(c)



(d)



(e)



(f)

FIG. 10. Modular robot concepts (a-f, left to right, top to bottom): miniature cable-driven surgical manipulator (Tesar and Elliot); modular manipulator concept based on hemispherical swash plate (Hamann); hybrid manipulator based on several 3-DOF modules; advanced servomanipulator (ASM) (Oak Ridge National Lab); Robotics Research dual 7-DOF arms; MIT telepresence ROV concept

quick tool interchange holder would also be necessary to make the device useful.

The concept [22] in Fig. 10(b) is an 8-DOF device made up of two 1-DOF elbows and two 3-DOF spherical swash plates (at the shoulder and wrist). It is not immediately apparent how each of the swash plates are to be driven, whether they can be made to be stiff and robust, and whether they can operate with low friction. Nonetheless, the spherical swash plate module deserves attention because of its compactness.

The hybrid manipulator concept [56] of Fig. 10(c) is a series of 3-DOF modules (one shoulder and a series of wrists). This configuration is perhaps the most compact of the serial systems in that 12 DOF can be packaged between three basic links and the end-effector. This level of flexibility allows for superior obstacle avoidance while providing sufficient dexterity to perform physical tasks even in a highly cluttered work volume and still retaining a substantial level of stiffness and load-carrying capacity. The system is equivalent to a series of ball and sockets (4) with three basic links whose location in space can be obtained by relatively simple iterative computations. Hence, this highly dexterous system is reasonably programmable by means of a structured software algorithm.

Perhaps the first modular robot is the dual arm system shown in Fig. 10(d), conceptualized in a 1981 design study [16] by Carl Flatau and built and implemented by the Consolidated Fuel Reprocessing Program [15] of ORNL. The system has all of its eight identical motor drives beyond the shoulder, using multiple torque tubes with gear reducers near the final drive point for enhanced drive train stiffness. Seven additional modules make up the system (tongs, wrist, elbow, etc.). Recently, a dual arm M-2 system by CRL was used with six specially adapted fixtures to remotely disassemble (in 4 h) and assemble (in 3.5h) one of these advanced servomanipulator arms. It has a 50 lb continuous load capacity through 6 DOF and uses digital control technology for its operation. Because all the electronics and motors are beyond the shoulder, it can be used in very demanding conditions (temperature, radiation, etc.). The complexity of the drive train geometry, however, prevents this robot from being considered as reconfigurable, although technical modifications (tech mods) are a relatively simple matter.

A more recent modular arm system [61] has been created by Robotics Research Corporation and is represented in Fig. 10(e) as a dual arm system of 14 DOF. In this case, harmonic gear reducers driven by brushless sumarium cobalt DC servo motors directly actuate each of the joints in a sleek aluminum envelope which can be rapidly disassembled by means of quick-disconnect band clamps. This system can be configured from 3 to 17 DOF with joint torque capacities of 150 to 17,000 in-lb., resulting in positional repeatabilities of a few tenths of a thousandth of an inch. For example, the 7-DOF model k/B-127 weighs 160 lb, is 4 ft long, and has a 20 lb payload and a positional resolution of 0.002 in. An initial effort has been made to make the system intelligent through a balanced criteria based decision-making software (a sampling rate of 50 ms) to treat energy efficiency, joint load balancing, improved force capacity, and so on. The cogging oscillations of the harmonic drive have been dealt with by an effective internal torque loop control about each actuator. The system clearly possesses real attributes. It is not intended, however, to treat the disturbance rejection problem since it is relatively "soft" in its drive train structure.

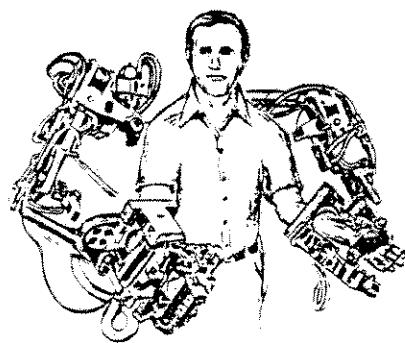
Finally, the MIT telepresence ROV concept [63] is

shown in Fig. 10(f). It includes multiple communication links with the command center, a warehouse of replacement parts, supplies, and tools, and not fewer than three dexterous robot manipulators. Obviously, this ROV is intended to provide in-orbit maintenance, repair, inspection, and supply capability to satellites or other space-based platforms beyond the space station. The system is truly complex and can not be considered as a near-term development intended to perform only simple assembly or repair tasks. To accomplish the level of technology implied in this concept could well require two full decades.

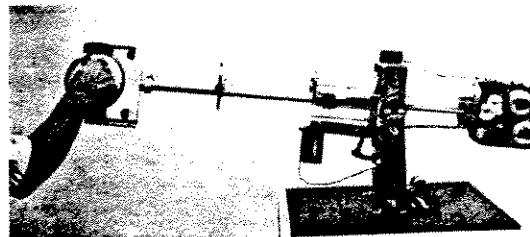
11. Manual Controller Architecture. The series of concepts shown in Fig. 11 indicate that manual controllers deserve their own intense development and architecture in order to best support the man-machine objectives that allow extensive human intervention and supervision of the robot slave system. The work at ANL established much of our early master-slave technology. During the 60s, however, GE attempted to extend that technology [3, 20, 30, 31] in several prototypes (Hardiman, Handyman, the walking machine, Man-Mate, etc.). The Handyman prototype in Figure 11(a) is their dual exo-skeleton manual controller to operate a pair of slave robots. Clearly, this early system was not optimum. It used a master whose geometry was identical to that of the slave except for size. This similarity allowed a direct one-to-one correspondence of the electrical signals (current, voltage, resolver, etc.) between the master and the slave. This simplicity meant that the force feedback was feasible even if it were scaled down to match the capacity of the operator. The problem associated with this arrangement is that a 6-DOF master could not control an 8-DOF slave, a slave whose geometry was different from the master, or a slave whose character changed during operation (to avoid obstacles, to enhance performance, etc.). Hence, both the master and the slave were reduced to the lowest common denominator—they were severely compromised and neither could be optimized with respect to their separate functions. Probably most damaging is the fact that a single standoff master could not sequentially control a mix of slaves. This need to have one controller (to reduce training effort, reduce confusion, reduce cockpit complexity, etc.) forces the development of a manual controller whose geometry is matched to the task of interfacing to the human operator. Then operational software must provide the signal transformations to make the control of any slave possible. This next generation of controller technology is represented in the examples given in the remaining concepts shown in Fig. 11.

The prototype in Fig. 11(b) has been under development for a decade at JPL by Bejczy [5]. It is essentially a pair of gimbals (2 DOF in rotation plus one slider at the shoulder and 3 DOF at the handgrip), driven through cables by actuators on or near the shoulder to make force feedback feasible. This system now operates with real time software and performs smoothly in its testbed. It is lightweight and almost frictionless. One of its limitations is that it does not fold compactly for stowage to reduce clutter in the cockpit.

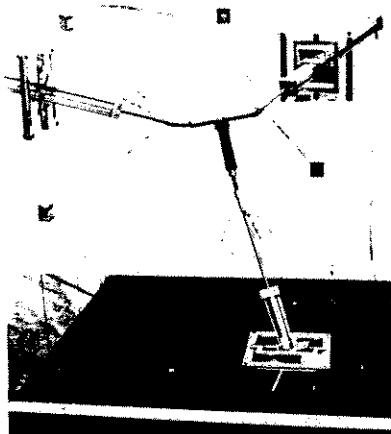
The nine-string handgrip manual controller [Fig. 11(c)] has also been under development [55,57] for a decade by Tesar et al (at the University of Texas at Austin). The length of each string is measured by a potentiometer. This length data for three strings attached to a point on the handgrip (to form a tetrahedron) can be used to calculate the point coordinates in the controller reference. This computation is very simple, is identical for each of three points, and can be done



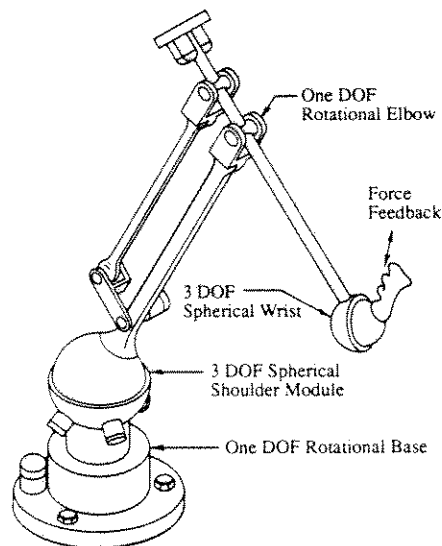
(a)



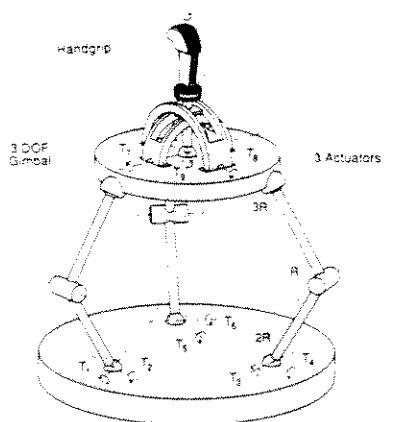
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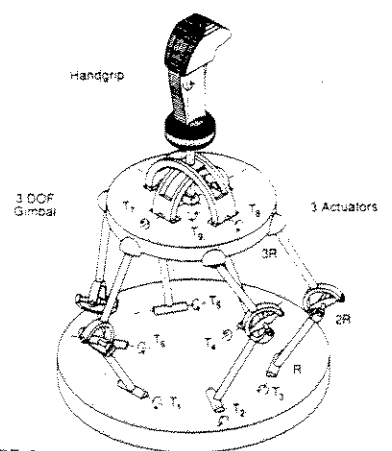
(d)



6 DOF, 3 Legged
Stewart Platform

6 Actuators

(e)



6 DOF, 6 Legged
Stewart Platform

6 Actuators

(f)

FIG. 11. Manual controller architecture (a–f, left to right, top to bottom): G.E.'s exoskeleton man-machine prototype; JPL's manual controller prototype (Bejczy); Nine-string force feedback manual controller (Univ. of Texas); 8-DOF universal manual controller (Tesar); 9-DOF redundant manual controller concept (Tesar and Kim); 9-DOF redundant manual controller concept (Tesar and Kim)

easily in real time to locate the handgrip in spatial coordinates. This set of coordinates can then be transformed (scaled, reoriented, filtered, smoothed, etc.) into end-effector coordinates of the slave robot. A force sensor on the slave robot wrist creates signals which can also be transformed to become effective forces at the handgrip. These handgrip forces are generated by a combination of constant pneumatic piston forces and variable (under servo motor control) string tensions. This set of force component transformations is relatively simple and can also be achieved in real time on generic laboratory computer systems. In addition, the signals from the manual controller can be sent to a graphic workstation to control a simulation of the robot in its work volume in real time. These systems are now fully interfaced and running in real time in the Texas testbed. Ghosting of the robot (predicting where it will be graphically before it actually moves) is also feasible in this system. This type of technology may prove useful in bridging the man-machine interface problems associated with master-slave signal time lags.

Under grant support from JSC, the Texas team is pursuing an in-depth architectural study of manual controllers since the next prototype could easily cost \$250,000. An early concept [25] is shown in Fig. 11(d). It is equivalent to an 8-DOF geometry. It has a vertical axis at the base, a spherical shoulder (3 DOF), an in-parallel driven elbow, and a spherical wrist (3 DOF). Given lightweight actuators (a real problem in these systems), this system would be lightweight, stowable, and easily portable (perhaps in a small suitcase). The reason for the extra 2 DOF is to provide choices for enhanced performance to better match the needs of the operator, to better represent forces to the operator, and so on. In effect, the system can be made intelligent because structural choices remain for the operator to improve the overall performance of the system.

Additional concepts [25] are under study [see Figs. 11(e,f)]. One is a three-legged Stewart platform (6 DOF) combined with a lightweight gimbal at the handgrip (3 DOF) to form a 9-DOF testbed prototype. The first six actuators drive joints in 2-DOF universal joints at the bottom of each of the legs. The system may be made exceptionally lightweight above the base plate if the handgrip gimbal is removed. Also, it can easily fold flat for compact stowage. Using carbon fiber links, high quality bearings, suitable ball and socket joints on the upper plate, and the very best of geared actuator design should produce a near optimum manual controller capable of exceptional performance and able to drive a slave in a stand-off position.

The prototype concept in Fig. 11(f) has six legs and a somewhat simpler actuator arrangement at the bottom of each leg. At first glance, the structure looks more complex than that in Fig. 11(e). A full study of the criteria (which are numerous) of operation in a testbed is essential to make a final selection.

MODULAR ARCHITECTURE FOR ROBOT STRUCTURES

The present generation of intelligent machines is subject to basic limitations that need to be rectified before robotics and other advanced manufacturing systems can be rapidly integrated into present-day operations. The University of Texas program is aggressively pursuing a modularity approach which could increase the market potential and decrease the

design cycle time of robots and similar precision machines. Modularity addresses the problems of precision, control, sensory perception, and design is such a way that near-term solutions are possible and long-term growth in intelligent machine systems can be assured.

Currently, lack of precision is a serious shortcoming in robotic applications. Even though positioning accuracy can be as high as 0.05 in., positioning under load can be disturbed as much as 0.2–0.4 in. due to flexibility in the structure. The associated deformation may be the result of dynamic forces which are usually known, or it may originate from task operations such as routing or force fitting which are usually unknown values. Jigs and fixtures constitute the current solution to this problem. However, since jigs and fixtures are product-dependent and expensive, they are a barrier to the CAD/CAM-database factory of the future.

Numerical control requires a precise control algorithm. No general mathematical formulation now exists for the control of manipulators of more than the most elementary geometries. Point-to-point programming is the most common form of task definition, and, since computations are not required to be performed on-line, real time control is not utilized. Intelligent control in the form of updates compensating for the changes in the work environment and loading can not be achieved until real-time formulation of a dynamic model is possible. The University of Texas team now has the full inertial and deformation model of a generalized 6-DOF serial manipulator operational on an Analogic AP-500 pipeline processor in 5.6 ms[64]. The system can also address an extended N -DOF serial structure [54].

Sensory feedback is widely accepted as one of the key components in research in robotics. As a result, important gains have been made in the fields of vision, tactile, force torque, and proximity detection. Force torque sensing is especially important for man-machine communications and enhanced machine intelligence. The exceptionally few such devices employed in present systems indicates the low level of machine intelligence currently available. Joint positions represent essential data in dynamic analysis formulations. Progress has been made on position encoders and resolvers. Unfortunately, high cost for the required high resolution remains a dilemma for designers today.

Because of the generality of motion during operation and the large number of system design parameters, the design of manipulators is an expensive, time-consuming and challenging task. The sheer magnitude [48] can be illustrated by noting that a generic 6-DOF serial manipulator (the simplest of all 6-DOF structures) can have as many as 18 geometric parameters, 42 mass parameters, 36 deformation parameters, and 18 actuator parameters. The design and development of such a generic structure can be expensive in terms of resources. The Cincinnati Milacron T3 series required \$7 million and 7 years of development to bring to production. The first shuttle manipulator was delivered [42] at a total cost of \$100 million. The next generation of shuttle manipulator is estimated to cost up to \$1 billion.

In order to allow designers and users to quickly assimilate advancements in technology and rapidly adapt to shifting market demands (hence to prevent obsolescence), a component approach must be applied to intelligent machine systems. Modular joints, prime movers, software, and sensors would simplify solutions to the present problems and allow flexible adaptation of new advances to existing modular systems. Systems could be updated without major disruption of production

in the workplace, and large capital outlays for modernization could be avoided.

The previous section of this paper presented a broad overview of the present character of robot structures pointing out the gradual integration of modules in this technology. The objective of this section is to show how a total architecture based on modularity can be created without reducing any choices left to the designer. This architecture must not exhibit any principal voids if it is to be productive in generating a higher and more complete level of understanding of robot structure. This completeness is the goal of this presentation.

1. *Undriven Joints.* All joints in a serial arm have to be driven by an actuator if controlled motion is to be achieved. On the other hand, parallel structures can be made of a mix of driven and undriven joints. The nature of these joints between adjacent links has been known to kinematicians since the time of Reuleaux (1876). Ignoring the screw joint, there are in total six such joints (see Fig. 12). The first is a simple turning joint, the revolute, shown in Fig. 12(a). The second is a simple sliding joint, the prism, shown in Fig. 12(b). Both of these joints provide 1-DOF constrained motion between neighboring links. Next there is the universal joint, which provides 2-DOF constraint between two links [see Fig. 12(c)]. It is the equivalent of two revolute joints in series (usually at 90° to each other). The other 2-DOF joint is the cylinder, which provides a combination of sliding and rotational constraint between neighboring links [see Fig. 12(d)]. In fact, it can also be represented by a series of one prism and one revolute joint. The next joint is the equivalent of a ball and socket and provides three rotational constraints between the two bodies [see Fig. 12(e)]. Taking three revolute joints in series such that their axes intersect at the center of the sphere provides the same effective constraint as the ball and socket. The final joint is the plane joint [Fig. 12(f)] which provides 3-DOF planar motion between neighboring links. This can also be achieved by three revolute joints in series if all their axes are parallel. This structural constraint approach is fully employed by such robot geometries as Duffy [13,14]. Kinematically, it is shown that every mechanical structure can be represented by combinations of revolute (R) and prism (P) joints. In other words, the architecture of robots begins at its most elementary level in terms of these two joints.

2. *Actuator Modules.* The next level of the architecture involves the development of three basic actuator modules (see Fig. 13). The first (Module M1) is a module whose axis of rotation (with a range of 270°) is intended to be perpendicular to the centerlines of the attached links [Fig. 13(a)] as in an elbow joint. The second (Module M2) has its axis of rotation (continuous) along the center lines [Fig. 13(b)] of the links (as in the human forearm). The last module (Module M3) provides a linear motion between the two neighboring links along their center lines [Fig. 13(c)].

Existing industrial drive systems usually include the following items: encoder, brake, motor, drive train, and joint bearing. Each of these is provided with its own heavy case, bearings, mounting plates, wiring interfaces, and so on. No thought has been used to integrate them into a combined whole to reduce weight, to make them more compact, to make them easily scaled, and so on. A vigorous effort is now underway at the University of Texas to provide this balanced integration as a first priority. The benefits of this development relative to the drive technology in present industrial robots can be estimated as

Criteria	Benefit
1. weight	3–10 × lighter
2. compactness	3–5 × smaller
3. stiffness	3–10 × stiffer
4. interfaces	2–4 × fewer
5. number of bearings	3 × fewer
6. redundancy	2 × greater

This listing of benefits could be continued. The most dramatic benefit is that of easily scaled modularity to create an extremely broad architecture of mechanical systems far beyond that which is now available. This means that a series of standardized elbows (1 DOF), knuckles (2 DOF), wrists (3 DOF), and shoulders (3 DOF) as system structural modules can now be designed in depth. Each DOF will require its own electronic module with standardized interfaces to the actuator module and perhaps a redundancy of 2 to enhance safety and to reduce downtime. These electronic modules would handle the encoder data, control the motor, monitor the brakes, obtain current and torque data from transducers, and so on, in addition to providing standardized interfaces to the system controller. Each of the actuator modules would be designed to have a semi-independent dual motor drive system to create a factor of 2 of redundancy throughout the system. Once the 1,2,3-DOF modules existed in standardized easily scaled units, then carbon fiber could be used in structural components such as links and undriven joints in a finite number of standardized shapes and sizes to complete the given mechanical system. DuPont has just announced a pitch-based carbon fiber which is five times stronger and stiffer than good steel. Because of the great weight reduction, this development suggests that structural components can also be dramatically improved with a possible benefit ratio of 5–10 times. Then a system controller and generic software system would be necessary to operate this generic architecture.

As a projection into the future, MIT has announced that ceramics having some ductility can be produced for superconducting applications (necessary for motor windings). In addition, materials scientists indicate that it is possible to use very pure copper at liquid nitrogen temperatures to obtain much stronger magnetic fields than are usually achieved in present electric motor designs. Hence, the actuator module should now be developed to take advantage of the potential for increased power density (perhaps by a factor of 4–5 times).

The potential combined benefit of all these distinct implementation factors is enormous. Considering the multiple benefits, the combined improvement factor would be between approximately 10^4 and 10^6 . This benefit ratio not only suggests that a revolution in mechanical technologies is feasible but that it could match the excitement now associated with microelectronics. It then becomes primarily a question of investment and strategy to make this revolution a reality.

3. *One-DOF Actuated Joints (Elbows).* It is now possible to show how to use the three actuator modules described in the previous section to drive all possible 1-DOF joints (6) which may be called "elbows" (see Fig. 14). The possible variations are:

- M1 inside Yoke*—The actuator module is contained in the volume of link 1 while link 2 forms a yoke on the outside of link 1. It forms a compact, simple assembly allowing up to 270° of rotation.

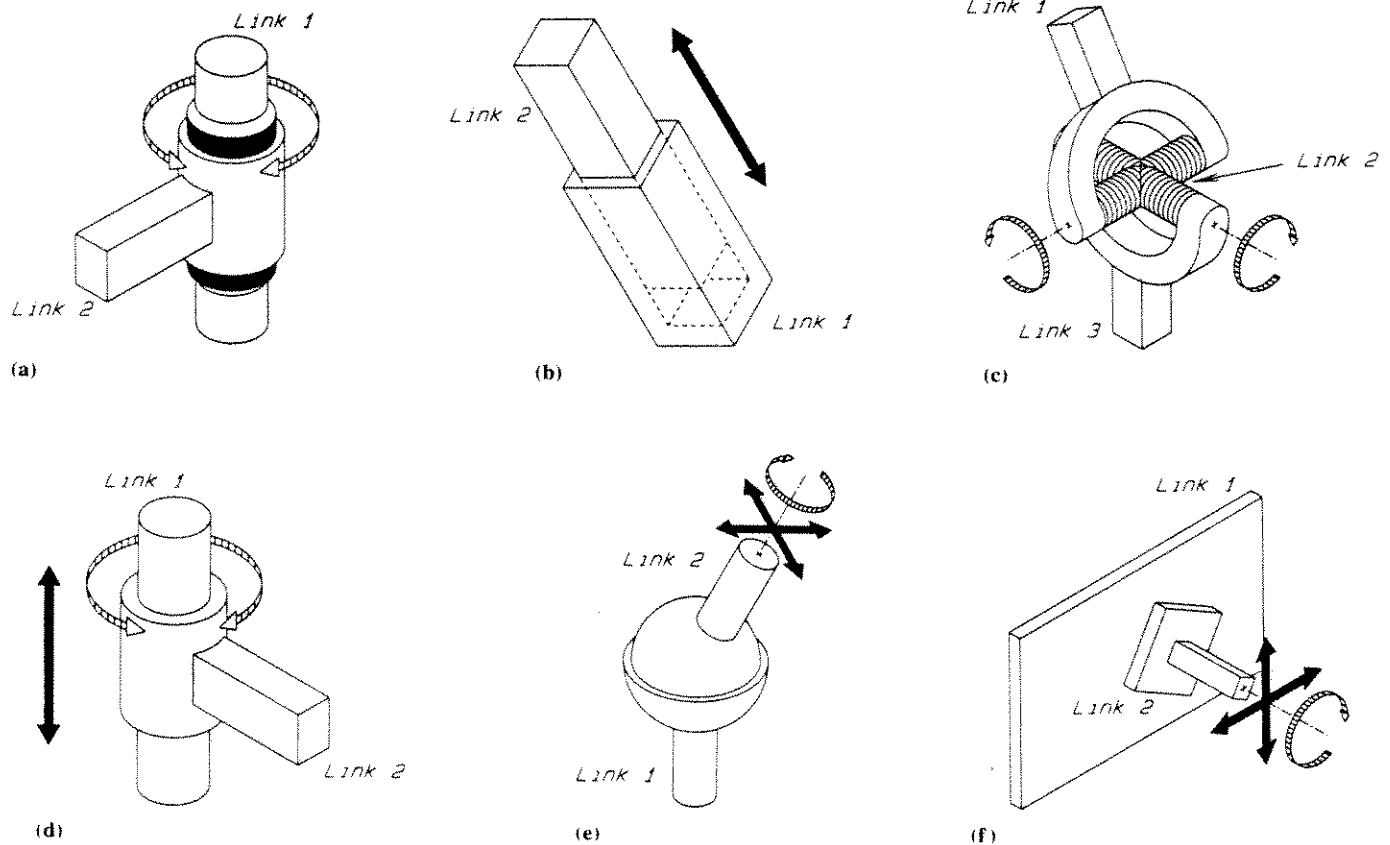


FIG. 12. Undriven structural joints (a–f, left to right, top to bottom): revolute joint (1 DOF); prismatic joint (1 DOF); Hooke's joint (2 DOF); cylindric joint (2 DOF); ball and socket joint (3 DOF); planar joint (3 DOF)

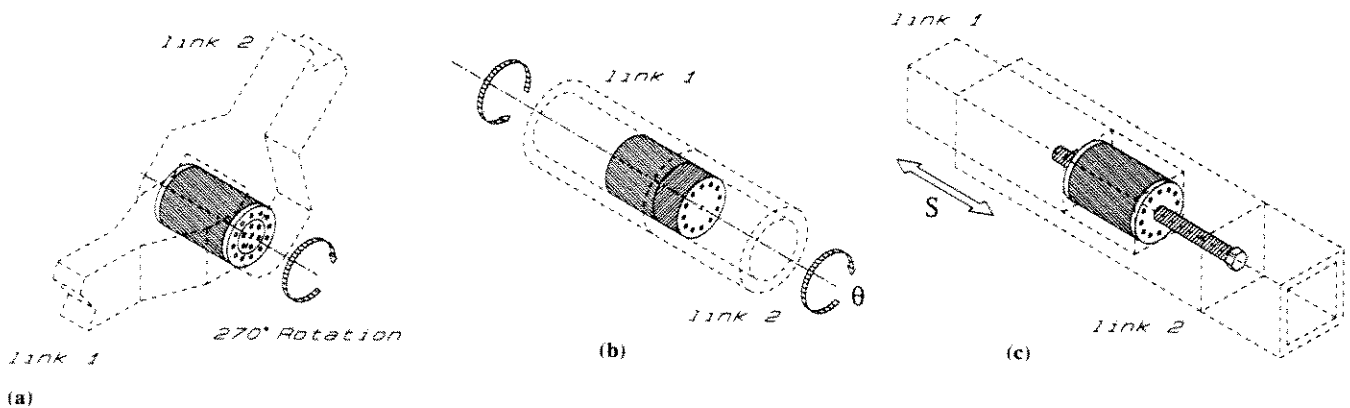


FIG. 13. Foundation actuator modules (a–c, left to right): models 1–3

- b. *M1 In Yoke Branches*—Divide M1 into separate halves and place in each branch of the yoke. The result is a compact simple assembly, providing 270° of rotation and somewhat more rugged than a above.
- c. *M2 Overlapping Links*—Continuous rotation of two links

as in elbow shown, in base of robot, in forearm, or last driver before the robot end-plate. Not as rugged as a and b above for the same weight. Relatively compact for exceptional dexterity.

- d. *M3 In Prism Joint*—Here, module M3 drives a slider

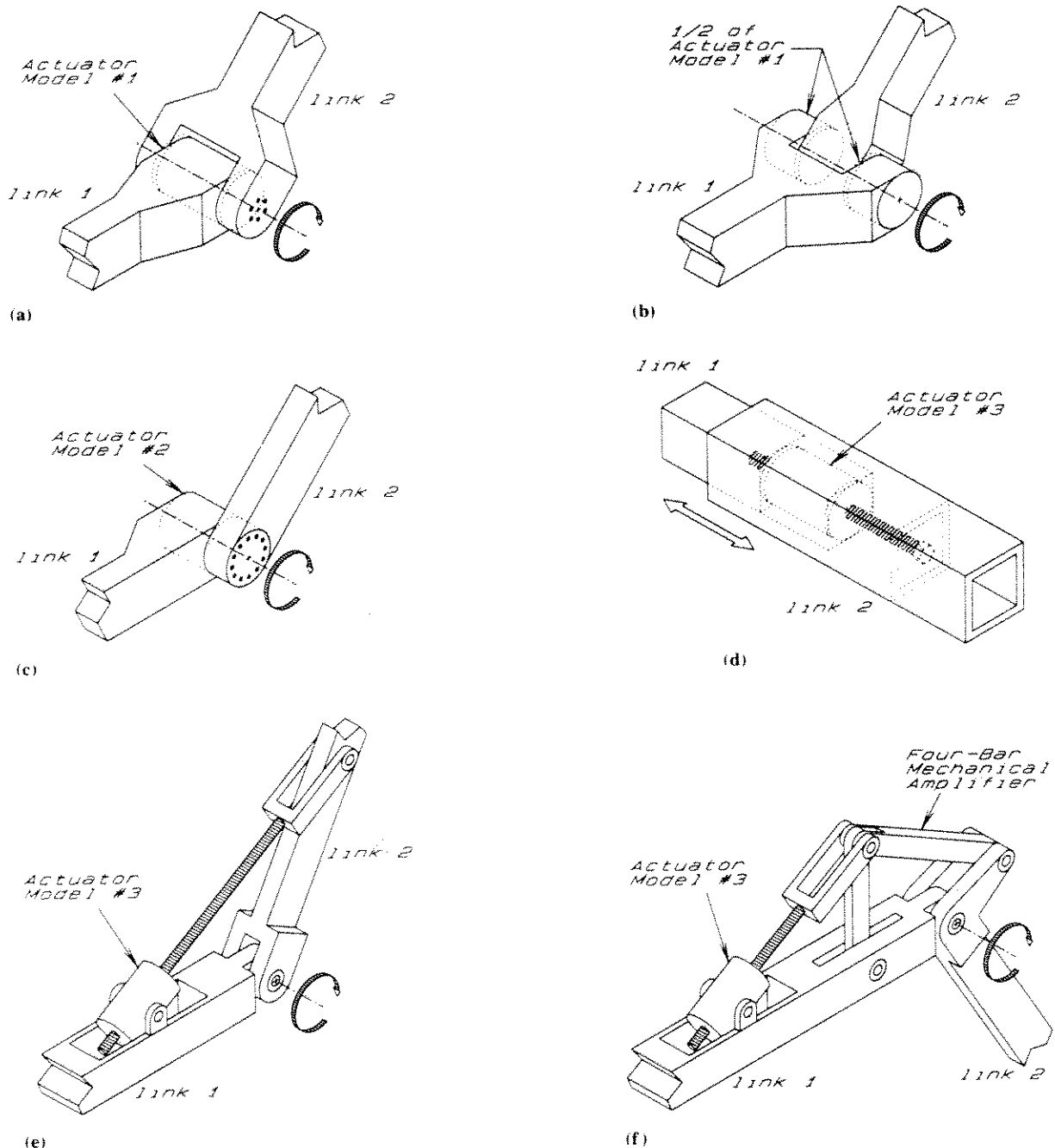


FIG. 14. One-DOF actuated elbow joints (a-f, left to right, top to bottom): elbows 1-6

joint by means of a built-in ballscrew. Special care must be employed to make the sliding joint light, stiff, and substantially frictionless.

- e. *M3 in Parallel*—Driver acts as an inverted slider crank mechanism in the same fashion as hydraulic pistons are used. This system provides about 140° of rotation. It is very stiff in the direction of rotation and can be used to resist large forces [as in backhoes, see Fig. 1(c) or heavy lifting systems, see Fig. 2(a)]. These systems could be

doubly actuated [Fig. 9(b)] but it would be difficult since the ballscrew is largely non-back-drivable.

- f. *M3 in Parallel with Linkage*—Here the linkage is used to amplify the output of the actuator to make 270° of joint rotation possible [Fig. 1(c)]. The system can be made very stiff but at the penalty of more bearings and links (more weight) and therefore it is less compact.

4. *Two-DOF Actuated "Knuckles"*. Knuckles can be thought of as devices which combine the relative motion of

three neighboring links in series. The first three examples (Fig. 15) are general, preserving all the link parameters (3) between the joint center lines. The second three examples (Fig. 16) show three isometric physical configurations where the revolute joints are perpendicular to each other. The first case (Fig. 15) will be described now.

- a. *Two Revolute Joints in Series*—Open chain of three links joined by two revolute joints (module M1) whose centerlines are located relative to each other by three link parameters. A common condition in robots is to have the two center lines parallel (only one link parameter remains). In this case, if link 1 is fixed, it is possible to use a point in link 3 to track an arbitrary planar curve (as with b and c below).
- b. *One Revolute and One Prism in Series*—Results in a common pair combining a revolute (M1) and a slider (M3) in series, especially if the joint center lines intersect

at 90° which reduces the number of link parameters for design to zero.

- c. *Two prisms in Series*—It is possible to use module M3 to provide linear motion between links 1 and 2 and links 2 and 3. When the angles between the joints are 90° , the Cardan coupling between offset rotating shafts results. This is frequently used as an x - y support structure in gantry robots. Extending this to three joints creates the common x - y - z system as used in the IBM robot. If all three axes intersect, the number of design parameters has been reduced to zero.

The unique configurations shown in Fig. 16 will be described next. Note that since the axes intersect at 90° , there are no geometric design parameters.

- a. *Two-DOF Gimbal in Rotation*—When the two serial revolute joint centerlines intersect at 90° , the result is a special geometry frequently found in robots. If the first

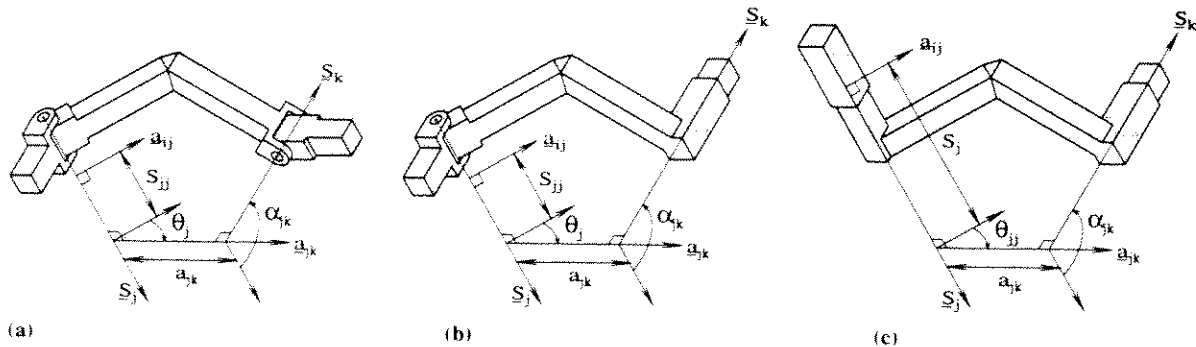


FIG. 15. Two-DOF general actuated knuckles (a-c, left to right): two revolute joints in series; one revolute joint and one prismatic joint in series; two prismatic joints in series

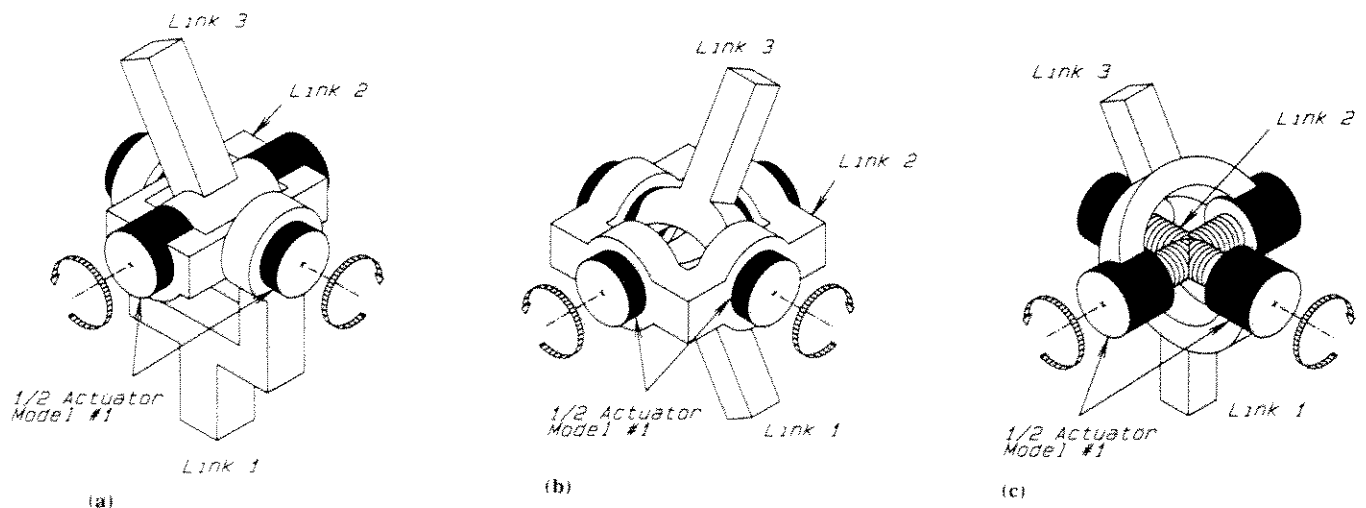


FIG. 16. Two-DOF knuckles with perpendicular axes (a-c, left to right): gimbal-based knuckle; exterior frame knuckle (based on universal joint); interior cross knuckle (based on universal joint)

joint uses two M1 halves in a yoke (link 1) and the second joint uses two M1 halves in an inner box structure (link 2), the result is a 2-DOF gimbal structure. The joint rotations between links 2 and 3 generally can not exceed 140° .

- b. *Actuator Modules in External Frame*—Put all four M1 half modules in an external box frame (link 2), each pair (on intersecting centerlines at 90°) driving an internal yoke on links 1 and 3. The operating joint rotations can not exceed 120° . This system structure can be made compact and exceptionally rigid and isometric. Each DOF could be driven in-parallel by module M3 if drive stiffness is a top priority [see Fig. 9(c)].
- c. *Actuator Modules with Internal Cross*—Attach all four M1 half modules to external yokes driving an internal cross member (at 90° similar to a universal joint found on vehicle drive shafts). This system is exceptionally compact but not as rugged as b above. Rotation cone of action may approach 270° .

5. *Two-DOF Parallel Planar Motion*. The objective is to create a rugged parallel structure which can follow an arbitrary planar curve. This is achieved by using actuators near the base joints of the system in order to reduce the moving mass of the system (Fig. 17).

- a. *Two-DOF in Parallel (Rotational Inputs)*—Combining two sets of two links [each with two rotary joints, Fig. 15(a)] to track the same point forms a parallel structure (known as a 2-DOF 5-bar linkage) with M1 modules at the fixed link pivot joints. This parallel structure is nor-

mally more rugged and involves less moving mass than the elementary serial structure. For example, the two upper links experience forces primarily along their center lines (two force members), which they can easily resist with small mass content.

- b. *Two-DOF in Parallel (Translational Inputs)*—If two serial systems such as those shown in Fig. 15(b) are combined to trace the same planar curve, the resulting system is a parallel structure in terms of an M3 module in each side of the structure. This type of structure is exceptionally stiff relative to forces acting on the tracing point.

6. *Three-DOF Planar Motion*. The relative motion provided by a plane joint [Fig. 12(f)] is the same as the 3 DOF which results when two flat surfaces move relative to each other (two in translation and one in rotation). This type of motion can be achieved in several different ways (see Figs. 18 and 19). The serial case in Fig. 18 will be described first.

- a. *Three Revolutes in Series*—Four links are joined by three rotary joints with parallel center lines, each driven by an M1 module. Fixing link 1 and putting the parallel centerlines vertical forms the 3-DOF SCARA assembly robot [by Adept in Fig. 2(c)].
- b. *One Revolute and Two Linear Joints*—Here, four links are joined by two linear joints (module M3) whose center lines intersect a rotary joint line at 90° (module M1). This is not a very common combination because of the weight and size of the linear joints.

The completely parallel planar motion devices in Fig. 19 will now be described.

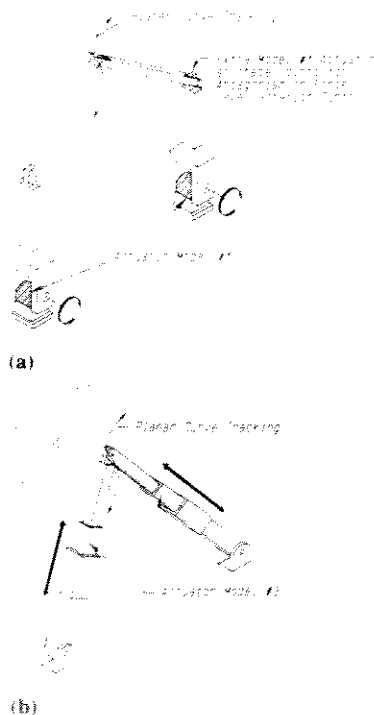


FIG. 17. Two-DOF parallel planar motion: (a, top) 2-DOF crank-operated planar curve structure; (b, bottom) 2-DOF slider-operated planar curve structure

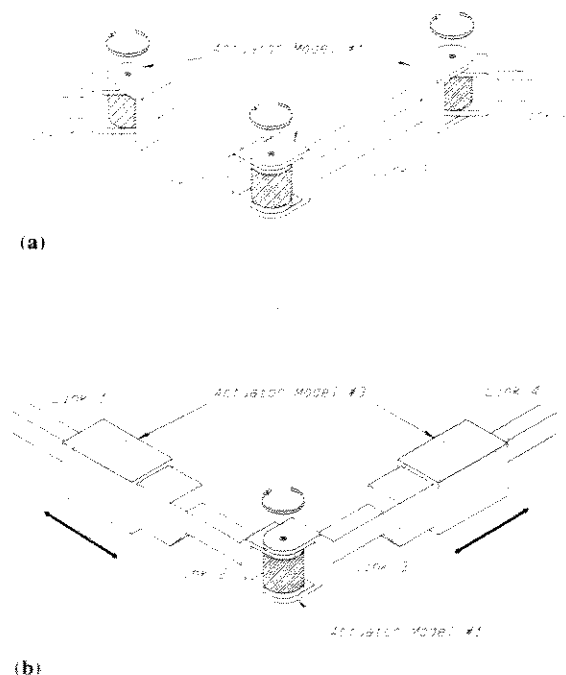


FIG. 18. Three-DOF serial planar structures: (a, top) 3-DOF planar serial structure based on three revolute joints; (b, bottom) planar serial structure based on one revolute and two prismatic joints

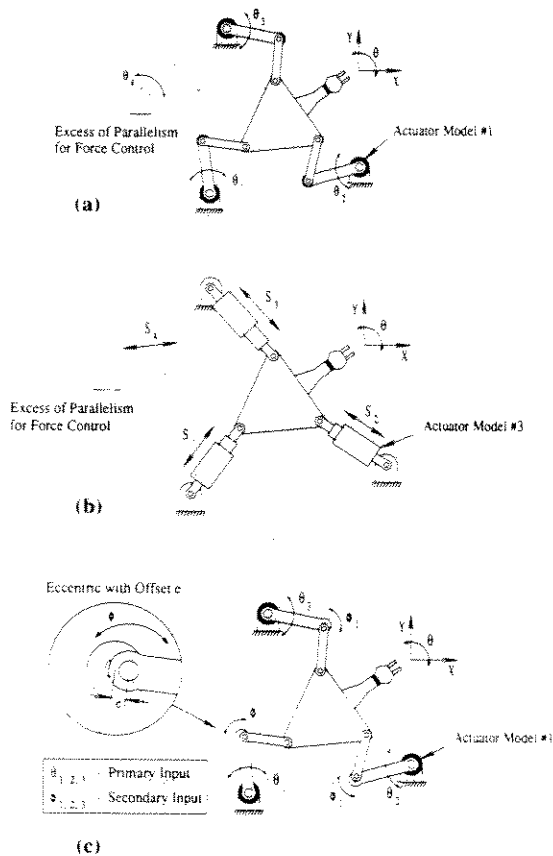


FIG. 19. Three-DOF parallel planar structures: (a, top) 3-DOF planar parallel structure with crank inputs; (b, middle) 3-DOF parallel planar structure with slider inputs; (c, bottom) parallel structure with three large and three small inputs for layered control

- a. *Three DOF in Parallel (Rotary Actuators)*—Consider a rigid triangle with each apex driven by a separate rotary crank (module M1) through a connecting binary link [Fig. 19(a)]. This is probably the ideal totally parallel planar mechanical structure. Note that all joint axes must be parallel to provide planar motion. Because all the actuators are on the fixed base, very little mass is moving in this system. Only the cranks experience significant bending deflections. The rest of the system is remarkably rigid against normal planar forces. The concept of “bracing” in the form of extra supporting structures (usually lightweight and used only on demand) can be used to stiffen an otherwise weak serial structure. The concept can be best understood in terms of parallel structures where it can be thought of as a part of an integrated and balanced design. Here, a fourth “leg” is added to allow a full time utilization of an extra input driver system (in-parallel) for improved force control. The control software then can use any three legs or all four if necessary to provide a significant improvement on the systems tracking capability under force disturbances.
- b. *Three DOF in Parallel (Linear Actuators)*—In this case, the rotary actuation system in Fig. 19(a) is replaced by three linear actuators (module M3). This forms a com-

pletely parallel planar 3-DOF robot system which is exceptionally rugged [Fig. 19(b)]. Again, an extra leg (in-parallel) can be added for improved force control.

- c. *Three Small Inputs for Layered Control*—The parallel system is ideally suited to putting in lightweight secondary actuators driving small eccentrics to create a separate small motion actuation system [Fig. 19(c)]. This system allows layered control to be part of the total architecture of the device. The concept can be generalized to all robot structures. It is ideally suited to compensate for small deformations which result from measured force disturbances on the structure and therefore to ensure a significant improvement in precision path tracking [49].

7. *Three-DOF Spherical Motion*. The simplest spherical motion is provided by a ball and socket joint. But this type of joint can not be driven directly. The following shows how to create spherical motion by using rotary actuator module M1. The first three examples are serial (Fig. 20).

- a. *Three Rotary Joints in Series*—Here, four links are joined by rotary joints driven by M1 modules whose center lines all intersect at the center of a sphere. Because of the large twisting moments involved, this structure is dif-

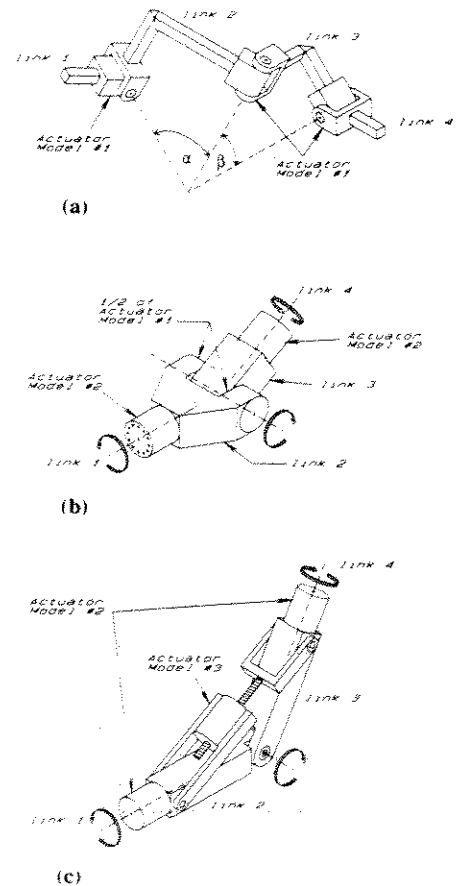


FIG. 20. Three-DOF serial spherical shoulders: (a, top) 3-DOF spherical serial structure; (b, middle) Compact 3-DOF serial structure (all spherical axes at 90°); (c, bottom) 3-DOF serial structure with central joint driven in-parallel

ficult to make rugged. If the angle between the succeeding axes is 90° , the system results in a common wrist configuration (used in the Kraft and IBM robots).

- b. *Three DOF Compact Shoulder (or Wrist)*—Put an M2 module on the base which drives a yoke (two M1 halves at 90° to the base center line) which then holds an M2 module inside the yoke. This is a very compact and rugged serial shoulder. The same series of modules can be used as a lightweight wrist at the end of a robot. Recall that to provide spherical motion, all axes must intersect.
- c. *Three DOF Compact Shoulder (Middle Joint Driven In-Parallel)*—In item b above, the yoke joint is driven in-parallel by module M3. This makes a very rugged and stiff shoulder, although not as compact.

The final two examples are completely parallel and may be thought of as the planar system shown in Fig. 19(a) wrapped on a sphere.

- a. *Three DOF Parallel Shoulder* [see Fig. 9(e)]—If three sets of serial links are used to drive the same output link (link 4), then a completely parallel shoulder module results where all the drivers (M1 modules) can be on the fixed link. A preloaded ball and socket can be maintained in the center of the sphere for load-carrying capacity if desired.
- b. *Three DOF Parallel Wrist* [see Fig. 9(f)]—Consider all the fixed axes of the shoulder to be concentric to form a wrist which can be driven through torque tubes along the center line of the robot forearm.

8. *Generalized Serial Structure.* The objective is to provide a general mechanical architecture by combining a series of links with 1 DOF joints in-between. This means that the weight of most of the actuators have to be carried by the moving structure. All forces, errors, deformations, and so on, are additive in a serial structure making it the least rugged and least precise of all possible architectures. To be general, each link will contain two joint center lines (having an offset (a), a twist angle (α), and a distance (s) along the link, i.e., three parameters; see Fig. 21). In most robots, the only variable is either the offset between the joints (when they are parallel) or the twist angle (when the joint centerlines intersect) which is usually fixed at 90° . The reason serial structures are used is that they provide a maximum level of dexterity, excellent obstacle avoidance, simplicity of force analysis and design, minimal intrusion into their workspace, small footprint, compact stowage, and so on.

- a. *All Rotary Joints*—Today, almost all serial robot structures use rotary joints. Some of the joints are driven by in-parallel ballscrews. The normal number of joints is six, resulting in a total of 18 geometric parameters to define the structure.
- b. *Mixed Rotary and Linear Joints*—Any combination of rotary and linear joints is possible in a serial structure. Excluding the screw joint, all mechanical architectures can be built from combinations of linear and rotary joints. This is why the most fundamental level of modular architecture can be driven by M1, M2, and M3 actuator modules.

9. *Generalized Parallel Structure.* Parallel structures have been known to kinematicians ever since the time of Reuleaux (1876). Such structures were enhanced in their importance by Stewart (1965) when he gave an in-depth presentation on what has become known as the Stewart platform.

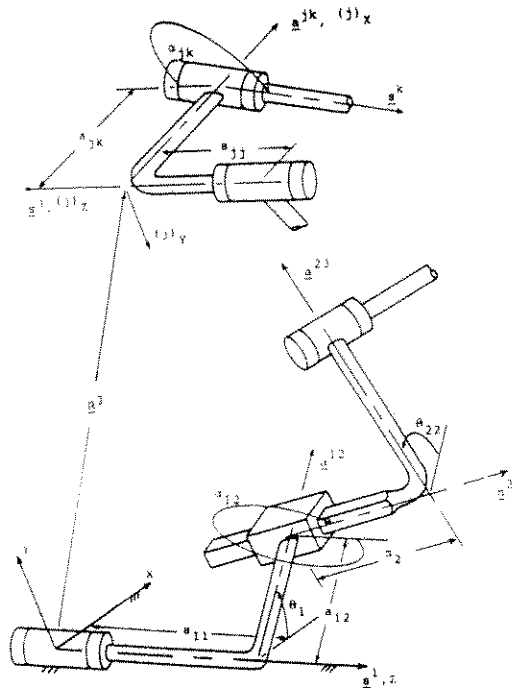


FIG. 21. Ultimate serial structure based on prismatic and revolute joints

Parallel structures have attributes quite different from serial structures. The input actuators can be distributed anywhere in the system where there is a DOF. The forces within the structure are distributed as are the errors (position, velocity, etc.), deformations, backlash, and so on. This means that no one part of the system becomes a "weak link" as can happen in a serial structure. In general, the parallel system can be made much more rugged with small effective moving mass and provide much higher precision motion tracking under force disturbances.

- a. *Stewart Platform (Six Legs)*—Each leg of the platform [see Fig. 6(e)] contains a hydraulic piston as a driver (or by module M3) as a driver. This system is widely used as the support for the LINK pilot training system [see Fig. 6(f)]. Each leg could be driven at the base by a revolute with a knuckle along the leg and a ball and socket where the leg joins the platform [see Fig. 11(f)]. This device can be miniaturized to make the University of Texas micromanipulator [see Fig. 3(f)].
- b. *Stewart Platform (Three Legs)*—Each leg is driven by two revolute joints at the base in a gimbal format [see Fig. 11(e)]. The leg contains an elbow and spherical joint at the top where it joins the platform.
- c. *Dual Arms*—Here the object is held by two 6-DOF serial robots to provide a dual or parallel structure with an excess of six inputs. Multiple arms can also be considered in a generalized parallel system [see Figs. 10(d-f)].
- d. *Hands*—Essentially, identical fingers (three or more) are used to control an object at its finger tips. Each finger may be driven by two or more actuators in series depending on the level of force control desired [see Fig. 6(b)].

- e. *Walking Machines*—Walking machines are composed of two or more identical serial legs with various numbers of drivers. The six-legged machine by Odetics contains three drivers in each leg. It is specifically designed to resist gravity forces [see Figs. 5(a-c) and 6(c)].
- f. *Generalized Parallel Systems*—Essentially a multiplicity of "legs", "loops," or combinations can be assembled and operated if it is considered that each joint is driven by an actuator for each equivalent DOF (see Fig. 22). If it is recognized that every joint in a serial system must be driven, it can then be considered as a subsystem of the ultimate parallel system (multiple legs, arms, fingers, etc.) where every joint is driven. This then allows for the development of a generalized mathematical description (see Freeman and Tesar [17]). Having the generalized description as a modeling tool enables the designer a maximum flexibility of selecting the best actuator locations in the structure. It further enables the software designer a means to balance the use of excess actuator inputs in the system in order to enhance the system's overall performance.

10. *Hybrid Structures*. The concept of hybrid structure is the combination of structural modules of 1-, 2-, or 3-DOF in a larger system. This level of modularity allows for optimum design of the individual modules, leaving the system design (with much fewer parameters) to a later stage in the development process.

- a. *Seven-DOF Modular Arm*—This arm is now becoming a standard where a 3-DOF shoulder and a 3-DOF wrist are separated by a 1-DOF elbow [see Figs. 3(a) and 11(d)]. The Robotics Research Corp. arm is of this type [see Fig. 10(e)].
- b. *Gantry Systems*—The first 2 or 3 DOF are rather long linear joints to form the gantry [see Fig 2(e)]. Suspended below this x-y platform is a 4-6-DOF arm. The combination allows coverage of a large work volume.

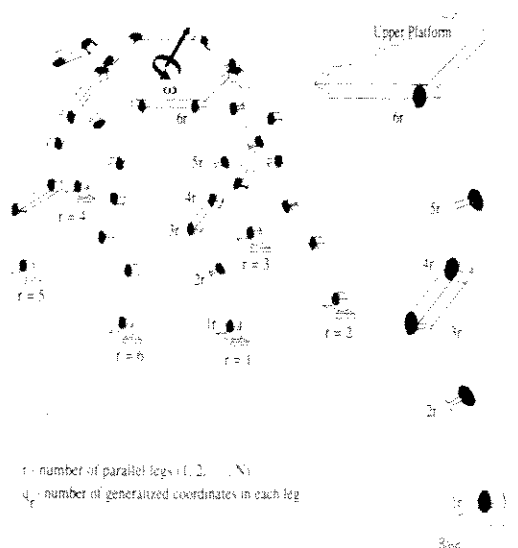


FIG. 22. Ultimate parallel structure

- c. *Nine-String Manual Controller*—The University of Texas' nine-string manual controller involves three modules attached to a handgrip at three points (in-parallel). Each module is a pneumatic piston constrained by three strings to form a tetrahedron [see Fig. 11(c)].
- d. *Snake Robot*—Several snake robots are now being considered. The Odetics concept involves 2-DOF serial knuckles combined in a series of 15 or more modules [see Fig. 4(c)]. The University of Texas concept involves a series of 3-DOF shoulders (the first is parallel, the rest are serial) to form a system of four modules and a total of 12 DOF [see Fig. 10(c)].
- e. *General Hybrid Structure*—The work of Tesar and Sklar [53] showed how to create a dynamic model for a manipulator structure (see Fig. 23) composed of a selection of parallel-driven modules (elbows, knuckles, wrists, shoulders, etc.). Once this level of modeling is achieved, the hybrid structure can be considered as a substructure of a parallel structure as shown in Figs. 3(e), 6(d), 10, and 11.

11. *Layered Scales*. The objective is to mix several scales of input to govern the total motion of the system. To be effective, the same number of inputs (six or more) must occur at each scale. The large motion might be thought to be at scale 1. The motion of dexterous fingers is at approximately a 10% scale relative to the scale of the human arm. Deformations are of the scale of 1%; hence, a set of inputs to match this would enhance precision and resolution. Finally, problems of electronic drift, temperature, and so on, might be taken care of by a 0.1% scale of inputs. This would then comprise a four-layered control system.

- a. *Cherry Picker Configuration*—Should a stable reference base be required within a large work volume while performing quite delicate and precise small-scale tasks, then a combination of a large 6-DOF transporting arm plus a lightweight precision manipulator, in series, to make what is called a "cherry picker," appears to be one alternative to an ROV. This configuration occurs frequently in nature, in high voltage line maintenance, and in the proposed Flight Telerobotic Servicer (FTS) for NASA. This scale combination allows the human to write, paint, and carve within a relatively large work volume without the need to move the shoulder.
- b. *Micromanipulator*—In this module, a parallel 6-DOF small motion device is attached to the end of the robot to provide a high resolution vernier motion system for enhanced precision and disturbance rejection [see Fig. 3(f)].
- c. *Control-in-the-Small*—Here, a series of small scale inputs (say at the 1% scale) is distributed throughout the structure [49] for a generalized capability for improved precision and disturbance rejection [see Figs. 9(a) and 19(c)].

CONCLUSION

The subject of architecture of robotics has been dealt with from the structural point of view with special emphasis on modularity. It is clear that modularity can be achieved at several levels (the prime mover, the structural module, number of DOF in the module, interface technology, etc.). The architecture which results maximizes the number of physical parameters still available to the designer so that he has a full selection within which to design (link dimensions between

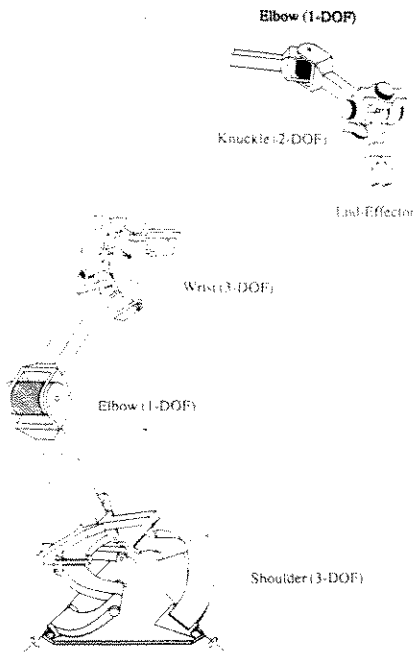


FIG. 23. General hybrid manipulator chain

modules, sequence of the modules, number of DOF in the sequenced modules, etc.). Of course, there are literally billions of systems which can be derived from the hundreds of design parameters available. Hence, a strategy for design must be developed which allows optimum results to occur in smaller, more addressable packages. This is the primary design argument in favor of modularity in robotics. The actuator modules (elbows, knuckles, shoulders, wrists, etc.) can now be treated as separate entities which can be designed in-depth, provided with generic interfaces, classified in terms of scaling rules, and so on. Once these packages exist in optimum units, they can then be integrated into a system which then would contain far fewer available design parameters and therefore becomes much more tractable to the designer. This versatility means that the designer would be able to consider a much broader range of options and would more likely take a top-down approach. Previously, the designer tried to make evolutionary changes in previous designs without having the capability to make dramatic changes which could provide enormous benefits.

There is also the threat of obsolescence. The designer fears that a heavy investment could result in a system which is obsolete or which can not rapidly adapt to emerging technologies. The model of the personal computer can provide a benchmark for the benefits of modularity in another system architecture. There, the original computers were dedicated mainframes each designed separately with little compatibility from one generation to the next. Today, the personal computer is highly modular, layered, interfaced at each level, and so on, in a nearly standardized format now recognized to be the low cost PC clone. Presently, robots are one-off designs with virtually no standardization. This results in a costly technology which conservatively uses new technology and may be

obsolete before it goes to production. Modularity would do much to reduce the level of cost (not initially) and would reduce the threat of obsolescence (allowing rapid changeover in favor of improved module technology). Modularity can thrive only if the full architecture which involves the integration of these modules is fully understood.

Finally, there is the question of investment, commitment, and strategy to make the outlined architectural revolution in the mechanical technologies a reality. Today, we have standard measures of success for the electronics industry (chip size, component density, algorithm benchmarks, cost of the PC, etc.). Based on these measures, the industrial decision maker can determine if his concern is competitive, if it is falling off the pace, and to some extent, what investment is required to maintain the concern's competitive stance. In the field of robotics, made up of one-off system designs, this decision process has no meaning. Until the system is broken down into measurable modules which can be integrated in several standardized systems based on a true architecture (i.e., as in the PC), decision-makers will not be able to defend an aggressive investment strategy or to measure their relative success. Of course, a similar need exists to formulate and support a national strategy to develop competitive technology for manufacturing. In 1987, the United States lost \$120 billion in manufacturing trade due to aggressive national policies in Japan, in Europe (especially after 1992), and in the future Russia, which has in place a \$100 billion 5-year plan for manufacturing. Fundamentally, the United States has to create a new level of excitement in its research institutions and to attract the best young minds to manufacturing, especially in the high value-added technologies. This paper has been written to show that a new emphasis on the mechanicals is now not only necessary but it will be rewarding and could be a major ingredient in a new competitive policy for manufacturing (and other applications). To take this process one step forward has been the purpose of this paper.

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THIRTY-YEAR FORECAST: THE CONCEPT OF A FIFTH GENERATION OF ROBOTICS- THE SUPER ROBOT

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Thirty-Year Forecast: The Concept of a Fifth Generation of Robotics—The Super Robot

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The purpose of this overview is to provide a balanced description of the present and future technologies associated with robotics. An accurate perception of this emerging technology is essential if decision makers are to commit the proper resources (laboratory, human capital, and development) to move the technology forward more rapidly and efficiently. Presently, it is contended that too much emphasis has been placed on singular component technologies and not on a strategic view of the system technologies and how a judicious integration of all of the component technologies can achieve results which are not yet forthcoming in robotics. The enormous growth in our computer technologies suggests that an architectural perspective for development of robotics would provide guidance to the technical community so that they can target rewarding research more effectively. For this reason, a condensed version of a fifth generation concept of robotics and its potential application range is presented in order to understand better today's existing technology. Then each major topic is overviewed with a listing of its associated component technologies, a highlight of what their level of technology is today, and a brief forecast of what that level might be in 10, 20, or 30 years.

ROBOT TECHNOLOGY TODAY

Robotics today is dominated by industrial applications where simple, repetitive tasks are performed reliably at relatively low cost. Most of these tasks are transfer operations moving products between machines which have specialized characteristics to produce high value in the product. The principal attribute of today's robot installations is their long life (20,000 h is the norm). This need for high reliability has forced designers to be conservative in the integration of modern technologies. Hence, the equivalent of fly-by-wire technology in our advanced aircraft is not represented by a similar technology of a

fully modeled and adaptively controlled dynamic system with aggressive computer (or human) decision making for critical operation of the technology at the highest possible level.

It is frequently argued that industrial robots weigh too much (some weigh more than 5000 lb), that they have poor dexterity (they are almost incapable of obstacle avoidance), that they require costly supporting equipment (jigs, fixtures, feeding mechanisms, and extensive engineering integration time and costs), that they cannot adapt adequately to changes in their environment (only a very limited use of force sensors and in some cases vision sensors), that they cannot respond to

process parameters (force disturbances cause deflections 20 times greater than their basic resolution), and so on.

All of these contentions are valid. By comparison to fantastic growths in the technology for aircraft, C^3 , telecommunications, and so on, robotics is a remarkably incomplete technology, much of it hardly changed from the technology available in 1965. Even though we see the highest quality of position encoders, their integration into an architecture of robotics is an afterthought. The geometry of robots looks either much like a lightweight numerical control (NC) machine or a human arm which leaves much of the potential architecture of these systems untouched or very poorly understood. Electric prime movers used in these systems were designed primarily for much less demanding applications; hence, their high weight, poor responsiveness, and low adaptability. The architecture of the computer controllers tends to be that which was frozen around 1975. Certainly, computer technology is being developed only incidentally for implementation in robotic systems.

The only conclusion can be that the state-of-the-art is far behind technical development in other fields, that an enormous opportunity for technical growth exists, and that an aggressive national development program is not only desirable but essential to meet existing and future industrial and military applications.

CONCEPT OF AN ADVANCED ROBOT TECHNOLOGY

The concept of an advanced (fifth generation) robotics technology represents the full integration of the most advanced computer technology (the supercomputer) with the most general mechanical architecture (serial, parallel, modular, etc.) to demonstrate an electronically rigid system (similar to our latest fly-by-wire aircraft) capable of rejecting process disturbances in real time while producing high value-added products on demand. This concept of an advanced robot is equivalent to the fifth generation robot system (1995 on) in comparison to the third generation (real time dynamic model reference control, 1980–1995) and the fourth generation (modularity in both hardware and software, 1985–2000). Today, high value-added operations are achieved primarily through the use of expensive, specialized and dedicated machines such as NC machines, automatic screw machines, wire bonding equipment for microcircuits, and so on, where the robot performs the low-valued function of handling of parts between these dedicated machines. By contrast, the fifth generation robot would be a fully integrated and self-contained generic machine system capable of performing a wide spectrum of precision light machining operations completely programmable by the designer of the product (shoes, clothes, appliances, etc.) and fully responsive to the individual demands of the marketplace. This vision of robotics by Issac Asimov is the heart of the factory of the future, yet it not only does not exist, technical resources to make it possible are either in short supply or have not been concentrated in a sufficient critical mass of expertise to make it happen.

Beyond the factory of the future there are applications of robotics to functions which involve hazards to humans such as space operations, operations on the ocean floor, ammunition handling under chemical or biological attack, processing of dangerous materials such as gallium arsenide for advanced microcircuit technology, nuclear reactor maintenance, and so on. In addition, special applications of real value to society,

such as microsurgery, have yet to be dealt with even in the research environment. The concept of the fifth generation robot being suggested here would lay the foundation to demonstrate a science of intelligent machines sufficiently general to treat all of these diverse and rewarding applications.

The following is a partial listing of applications which would become feasible or would be dramatically accelerated by an aggressive development of a fifth generation technology:

1. nuclear reactor maintenance,
2. precision light machining,
3. micromanipulation at very small scales,
4. microsurgery,
5. ocean floor operations,
6. space station operations,
7. battlefield operations,
8. 50-g centrifuge robot,
9. rapid runway repair even under attack,
10. remanufacture of military hardware such as jet engines, airframes, and so on,
11. walking machines and cooperating robots,
12. human augmentation for the handicapped.

TECHNICAL OBJECTIVES OF AN ADVANCED ROBOT TECHNOLOGY

Over the past several decades, the electronics, computer science, and software research communities have made major strides forward in their technical depth especially enhanced by strong pulls from the civil and defense sectors. The massive technological growth in microelectronics goes without saying. Emerging technologies such as artificial intelligence (AI), computer architectures (neuronets, parallel processing, etc.), simulation workstations, machine vision, and so on lead us to conclude that new opportunities exist to expand the system technologies of robotics itself. Nonetheless, until we have dedicated architectures targeted just to the exceptionally complex system of robotics, little will be achieved. For example, even though "expert systems" are being made available to enhance decision-making, that which will be required for robotics will face hundreds of computationally complex criteria, most of which are yet unknown. The reality of this class of task is heightened if we ask that we achieve a prioritized decision among these criteria in less than 30 ms.

By contrast, mechanical technology has not kept pace such that it is now perceived as a weak partner. Unfortunately, the mission objective of intelligent machines will require a marriage of many of these technologies, including the mechanical. Much of the mechanical design philosophy in the United States derives from a period during which farm machinery, power plants, construction machinery, automobiles, airplanes, jet engines, and so on were brought to a high level of development. Much of this design is performed in terms of compartmentalized rules (the basis of an art and the opposite of a science) which are based on negative criteria (noise, wear, fatigue, instability, vibrations, mean time between failures, etc.). On the other hand, the factory of the future demands the use of operational criteria associated with the quality of the product of the machine which implies precision (rarely dealt with as a first priority in the academic world). The positive criterion of precision involves the control of the output of the machine to specified tolerances regardless of the disturbances generated by the operation. To date, not a single

robot operates in terms of a real time dynamic model based on an accurate description of its system parameters in order to reject disturbances (i.e., the concept of closed loop operation found in fly-by-wire aircraft). Furthermore, the negative design criteria of failure in the operation of large machine structures of the past (textile machinery, battlefield materiel, etc.) have little to offer for the design of precision microprocessing equipment of the scale suitable to microsurgery or microcircuits. Hence, relative to the level of technical integration required to meet future needs, no balanced science of intelligent machines is being developed.

The simplest robotic architecture is a 6-degree-of-freedom (DOF) serial system (one link, one joint, one link, etc.). To date, two basic geometries have emerged. One is a structure similar to a coordinate axis (X-Y-Z) machine and the other is similar to a human arm. These simple structures are used because they represent very few design parameters and are designed primarily by intuitive means. The general 6-DOF serial robot system is described by 18 geometric, 42 mass, 36 deformation, and 18 control parameters (a total of 114) and represents a design complexity far beyond the means of existing expertise in industry. Beyond the serial structure, there are parallel structures (walking machines with four or more legs), redundant structures having excess prime mover inputs or excess degrees of freedom, modular structures to form systems from building blocks the way we now create computer systems, and so on. What this means is that the *design techniques for most future robotic systems do not yet exist* and can only be developed by a very aggressive research program.

Similarly, no industrial robot operates in terms of a real time dynamic model description to close the loop relative to the process it is performing, which may generate significant disturbances in the system. This means that precision light machining operations such as drilling, routing, milling, and so on cannot be performed by reasonably sized generic robots to the level of precision required. Disturbances due to forces equivalent to the specified load capacity of these robots can easily cause a deflection 20 times as great as the error represented by its repeatability (i.e., a 20 to 1 robot). The goal must be to measure these disturbances and to compensate for the resulting deformations (in order to maintain the desired level of precision) by means of a complete dynamic model evaluated in less than 10 ms (real time) by using the most modern computational hardware and software. *This class of control would be equivalent to feedforward compensation* (a technique now found in the very best Japanese Hi-Fi equipment) *and is what is meant by an electronically rigid robot system.*

ROLE OF ROBOTICS IN THE FACTORY OF THE FUTURE

Today, the drive to establish the factory of the future has led to vigorous development activity associated with CAD/CAM. Unfortunately, almost all of this activity is centered on the use of a collection of dedicated machines each capable of a limited number of distinct critical precision functions which must be sequenced to create the finished product. On the other hand, the fully integrated self-contained intelligent machine which is capable of producing broad classes of quality products fully responsive to the individual consumer does not exist in any form. In fact, the use of 30,000 robots in the USA at this time implies a penetration into the manufacturing

workplace of not more than 1 in 500, showing that robot implementation is far below what it could be. This low level of penetration may be due partially to the fact that each of our major firms (IBM, GE, GM, Westinghouse) made one robot and then decided to purchase robots from outside vendors or to buy subsidiaries either in Japan, Europe, or the USA. By contrast, in Japan, each of the major manufacturing firms (Hitachi, Mitsubishi, Fujitsu, etc.) make their own robots. The contention here is that US firms do not have the necessary in-house, balanced technical resources to remain competitive in this leading edge technology and are leaving it to their economic competitors. This lack of response to the threat of the trade deficit, exceeding \$120 billion in value-added products, is at the heart of the present proposal. The goal is to employ existing component technologies (the supercomputer, computer vision, digital control theory), enhance emerging technologies (expert systems, artificial intelligence, metrology, mechanical architecture, computer architecture, CAD/CAM), and fully integrate them by means of a balanced science for intelligent machines. The superrobot would be the most aggressive demonstration of this objective.

BRIEF DESCRIPTION OF CURRENT ROBOTIC TECHNOLOGIES

Computer Control Systems

The computer acts to coordinate and balance all functional activities in the robot. Increasingly, these functions are non-deterministic and may represent widely varying choices to meet task requirements. These task requirements may be derived from on-line access to a data base or they might come directly from human intervention. Some task requirements will require global task planning while others will require meeting precision motion specifications while being impacted by significant internal or external disturbances. Because of the highly nonlinear and highly coupled nature of the mechanical structure, feedforward modeling is essential to integrate high level sensory information in order to compensate for deflections, to avoid obstacles, to perform multiple arm tasks, and so on. Hence, computer hardware and software are at the heart of the operation of all robotic systems.

Hierarchical Control Systems

Because there are numerous layers of functional activity (sensors, actuators, and end-effectors, localized disturbance rejection, sensor data integration, etc.), it becomes essential to create a formalism to structure decision making and control; that is, hierarchical control. At least a decade of activity at the National Institute of Standards and Technology (formerly the NBS) has resulted in a modular, layered, parameterized format to prescribe interaction above, below, and within each layer with assignable time constants. These layers may be in parallel or in series, depending on the larger system architecture. Their interfaces are well defined and standardized.

Forecast. This technology will be described in a fully adaptable mathematical structure within the next decade. Major hardware dedicated to this hierarchical control structure will become standardized with various levels of complexity. Finally, within 2 decades, an interactive software will be available to parameterize all levels in the structure to meet specific architectural and task requirements.

Machine Intelligence

Today's robot controllers have failed to keep pace with the rapid development of computer technology. Frequently, manufacturers have spent extensive resources to develop one-off controllers that were reliable but technically out-of-date or obsolete, making advanced software implementation impossible. This one-off approach has dramatically limited growth in robotics overall. These systems are not adaptable and respond to task changes poorly. They do not learn the way people do. They cannot draw analogies. Increasingly, the growth of computer architecture suggests that this class of adaptability will eventually be feasible for robotic systems.

Reasoning/inference. Machine intelligence is founded on inference, the ability to deduce a fact not explicitly stated. By taking advantage of a computer's ability to make an inference, we can retrieve information that was only implicitly stored in its data banks. The machine must have stored both a rule of inference and the data on which to apply the rule. This inference structure is central to machine intelligence: the ability to diagnose a system fault, plan a course of action, or execute an action. Imagine hundreds of rules arranged in a decision tree. Heuristically, no optimum path through the tree can be expected; yet a desirable or appropriate solution can be achieved. Rules can be derived from a data base, a knowledge base, or they can be obtained by "learned" experience in operating the system.

Forecast. The growth of higher speed (50 mips) multiple and parallel processing architectures suggests that decision trees will be structured to "match" the processor architecture and vice versa. Modularity in hardware, software, rules, and interfaces will be the key. This class of technology will be extremely demanding and may require a full 3 decades to reach maturity.

Sensory perception. The sensory system monitors the robot and provides feedback information on the state of the environment and the robot itself. The task of the sensory system is to deal with predictive, incomplete, and conflicting information. To predict a future state can only be achieved in terms of a carefully formulated model reference of the system and its operation. The obtained data may be excessive, imprecise, or incomplete; yet it must be reduced and interpreted for use by the decision-making part of the system. It will be increasingly common to have conflicting data from the sensors whose resolution into a balanced data set is called sensor fusion.

Forecast. Increasingly, sensors will be implemented at the microchip level with on-board integration of signal amplification, analog to digital conversion, linearization, data reduction, thresholding, and so on on the chip. A recent chip accelerometer provides a factor 25 times the sensitivity of a typical piezo-resistive device. Standardization of field connections, software interfaces, and so on will be necessary to accelerate this development. The goal is to make sensors as inexpensive and lightweight as computer chips, which are then to be applied in excess to the robot structure and to fuse them into an adaptable hierarchical feedback system.

Software Systems

Robotic systems pose all the current challenges known to computer science. They must operate across multiple heterogeneous computer systems in a distributed and parallel fashion. They must contain sophisticated data bases and world

models that are updated in real time from several sources while they continue to be used for mission-oriented performance, and so on. Robotic systems are stretching the state-of-the-art in software and they make excellent test beds for new developments.

Object oriented systems. In traditional software systems, programs were active but the software itself was passive. The range of tasks that might face a robot system suggests that the software be actively adaptable. Object-oriented data systems are just a first step in reaching this level of flexibility. Clearly, the new type of data will require new object or task language systems.

Forecast. Parallel architectures will make a new paradigm for software development feasible. Integration of the hardware and software development process as an entity will become a reality. The designer-user will develop software that provides multiple links among defined types of information and various levels and location in the structure. This concurrent designer-user approach may likely require a full 3 decades to mature.

Intelligent data systems. The principal objective is to document accurately all essential characteristics of the operating environment of the robot in a "world model". This type of data is increasingly becoming available in terrain maps, nuclear plant models, chemical plant models, and so on. A related issue is the integration of multiple data bases into a single distributed information system (the retrieval of required data, its updating, its deletion, etc.)

Forecast. World model development will continuously require attention. Significant progress is being made. Unfortunately, as the data become more extensive, retrieval and update techniques will become serious technical developments. First level world models should be available within the decade. Procedures for their efficient utilization and automated modernization will require another decade.

Software. Clearly software is the basis for decision-making within the robot structure. It must be fast, reliable, redundant, fault tolerant, modular, layered, and so on. Software can not be developed independently of the operating system it is to run on. Testing and qualification is emerging as a major issue.

Forecast. Not only will the integration software and operating software become concurrent, but the architecture of the mechanical structure will be developed concurrently with the software architecture. This level of integration will require a form of interdisciplinary action largely missing today. Hence, complete architectural development is expected to require a full 3 decades.

Computer Architecture

The pervasive need (and benchmarking) for speed in computation is driving computer architecture today. Only recently have valid new architectures (multiple processors) become available. It is predicted that, in 1989, a 32 processor architecture (each capable of 50 mips) will become available. This massive development will have an enormous impact not only on robot operation but also on robot design.

Forecast. Systems of hundreds of processors (each of 10 mips or greater) will be available at reasonable cost within the decade. Systems of this class will be hardened, portable, and relatively low cost within 2 decades. Design in terms of hundreds of parameters will become feasible, thus

dramatically increasing the available generality of robotic systems.

Communications

Communication mismatches will plague robotic system integrators until the development and acceptance of appropriate standards. Complex robotic applications will be expected to integrate and organize information from hundreds of computational sources. But communication technology is evolving quickly to meet the needs for greater speeds and capacity in communication channels, making standardization elusive. Reliability and redundancy are critical design factors for robotic systems that will operate remotely or in battle. Communications interfaces span tightly and loosely coupled systems, grow more challenging with increased complexity and multiplicity of computers in the robotic system, and are even more challenging in the military arena of hazardous environments, remote operation, and critical functionality without breakdown.

Forecast. Unless a major industrial or federal body intervenes to establish communications standards, the present difficulty in interfaces will grow worse in relative terms.

SENSOR SYSTEMS

The sensory system has the simply stated job of sensing the environment, and providing "data" to the computer control system. The type of data required, the difficulty of converting it from data as sensed (large amounts of data) into digested and usable data for the control system, is a function of the complexity of the task to be performed, and the robot itself. It is, for example, the task of the sensory system to let the control know where the components of the robot actually are (vs. some planned location). It is also the task of the sensory system to sense the environment. This latter task can grow almost infinitely complex based on the task for the robot and the environment. Imagine, for example, the difference in requirements for a sensory system on a robot which is welding car bodies in a fixed location in the factory, versus the mobile battlefield robot which is refueling trucks, or unloading ammunition under adverse conditions in a war zone.

Force and Position Sensing

Increasingly, the robotics community is relying on low level sensing (position errors measured through vision, range finders, capacitance, acoustics, etc.). What is really needed are higher levels of information (force, velocities, accelerations, jerks, etc.) which are higher order properties in the model reference which, when integrated (in real time), can be used to predict the condition of the system at the lower level and therefore compensate for it directly through feedforward commands to the control system. Sensor fusion at this higher level can only occur if the model (or plant description) is available at that level in real time.

Forecast. As described above, distributed chip scaled sensors with on-board intelligence are now being developed. Their development to higher order signals (velocity, acceleration, jerk, shock, selected harmonics, etc.) will occur in this decade. Integration into the architecture of the robot system and its decision-making software will require another decade.

Imaging Sensors

An imaging sensor captures an array of data. Each location in the array represents an individual sensor value. Each value in the array of a TV image might represent a gray scale value, representing the light reflected toward the camera. The signal may be derived from temperature, radiation, sonar, force (tactile), potential fields (magnetism), and so on. Image processing can be divided into two forms: low level without scene knowledge and high level, which benefits from advanced knowledge of the scene. Obviously, this processing implies specialized computer hardware and software. This is an intensive field of activity at the present time.

Forecast. Success in the next decade will be highly dependent on foreknowledge of the scene as might come from a world model. Aggressive image analysis technology development will be required if significant progress in the second decade is to occur without scene knowledge. Finally, real time analysis will probably go into the third decade.

Image and Speech Understanding Systems

Significant breakthroughs in understanding software will be required before a robot can be provided with capabilities even remotely matching those of a human in general adaptability and applicability. These needed breakthroughs are centered in the field of AI. Thus representation, memory size, and speed-of-search are all obstacles to current systemic capabilities. Presently, machine vision is being used in factory inspections and speech recognition systems are increasingly useful for human machine interfaces.

Forecast. The next decade will see continued progress on signal analysis in digital form with differencing relative to world models, a real possibility in machine vision. Speech understanding should be successful in a digital format in this decade. Equivalent analog scene evaluation in the human sense will evade researchers for the next two decades.

Other Sensors

In the future, excess of sensor information is almost certain. These data must be reduced to a minimal number of key requirements for system response. Today, robots are highly deterministic, except in their ability to respond to global process requirements. It is contended here that future mechanical architectures must be designed to absorb the reduced commands obtained from a broad range of sensors. If not, then advances in sensor technology will have no outlet. This includes the concept of adaptive control but it also means that the geometric character (distributed degrees of freedom at several scales) of the structure must match the hierarchical nature of the sensor system.

Forecast. This decade will show that the mechanical and electrical disciplines will have to match their input-output architectures in order that process parameters are responded to by the robot system.

ACTUATION SYSTEMS

The actuation system here implies the mechanical structure, including prime movers, links, bearings, and so on, which is capable of performing physical tasks. Usually, this system is thought of as a manipulator. It may have only 1 degree-of-freedom (DOF), or it may have as many as 20 DOF. It may

be serial (one link, one joint, one link, etc.), it may be parallel (like a legged platform of several identical legs), or it may be a hybrid of these. The main objective of the actuation system is to accurately transform a computer command signal into a physical operation, such as motion, force, or any combination of motion and force.

Structural Geometry

An architectural issue is the balance of serial and parallel mechanical structures. Almost every existing robot is serial. Yet precision control in biological systems are almost always parallel (the extraordinary precision of the motion of the human eye). The Stewart platform (represented by the Link trainer for pilots) is one of our simplest parallel systems, and it has attributes completely different (load capacity, stiffness, distributed error instead of accumulated error, etc.) from serial structures (high dexterity, simple assembly, compactness, etc.). What is needed is a set of architectural rules which allow the designer the best mix of serial and parallel structures for 3-, 6-, 12-DOF systems, and beyond depending on what the system application range is intended to be.

One of the most demanding operational tasks faced by the robotics community is the precision interaction of two (or more) similar (or dissimilar) arms. Walking machines can be made up of two, three, four, or more interacting legs. Hands with multiple fingers are being considered. In repair operations (especially in space and in microsurgery), there will be the need for dual arm operation (6 degrees of freedom each). Basically, the system represents an excess of inputs (say five) from a total 12 degrees of freedom (DOF) which allows for a precision 1 DOF interaction between the end effectors. Then all operational criteria must now be satisfied by internally balancing a total of 12 inputs against 7 independent outputs.

This balance has to occur in real time and essentially means optimization in 30 ms. Many classical optimization problems of this magnitude take hours of computer time. Yet a strategy must be developed to meet this operational need or dual arm systems will not be able to perform many functions they are now being considered for.

Forecast. One of the most demanding aspects of existing factory devices is their specialized nature to meet specialized needs. This high level of specialization makes for a large collection of unique control systems making more interfaces necessary and making these interfaces incompatible. Hence, a generic mechanical architecture which results in fewer specialized machines which are more flexible and adaptable would reduce the interface problems we now experience in our factories. Generic mechanical systems will evolve as a meaningful architecture during the next decade.

Structural Dynamics

The dynamic model of the robot is essential in order to complete its control system. This means that the complete dynamic description must be obtained in less than 30 ms and preferably in 5. This is increasingly possible on pipeline processors (cost today of \$20,000) and should be available for extremely low cost 30 years from now. This means that the central concept of model referencing and feedforward control (the opposite of feedback control) will soon be feasible. Feedback can not be expected to operate increasingly more complex systems which are highly nonlinear and coupled. Hence, sensor feedback can only be used to correct the inaccuracies

of the feedforward model and the unmeasured disturbances in the unit process faced by the system.

Off-line programming implies a complete numerical awareness of the machine system including all geometrical, mass, control, temperature, drift, deformation, and other parameters. Otherwise, the computer can not drive the system except to meet the simplest of functions (of low value). Without computer control, access to the data base is lost and the factory of the future fails. Hence, off-line programming implies a level of metrology virtually unrecognized by the community. This metrology will eventually have to be available at the worksite to identify new parameters introduced by repairs, "tech mod," or software changes. In the meantime, careful laboratory development of robot metrology is essential to characterize fully the state-of-the-art and project R&D requirements into the future.

Forecast. The dynamic model for deformable robot structures will become available on parallel computer architectures in 5 ms sampling rates within this decade. A full metrology technology will also evolve in this decade. The adaptive control of these complex systems will not mature until the second decade.

Actuation Mechanisms

The driver of the mechanical system is the prime mover (electrical, pneumatic, hydraulic, etc.). This prime mover is increasingly sophisticated electric servo motors. Some of these are direct drive without gear reduction. Virtually no work has been done in recent years on lightweight, stiff gear reduction mechanisms. Another question just emerging involves the number and distribution of actuators within the mechanical structure.

Forecast. During this decade, mechanical manipulators will be designed to contain an excess of input prime movers for input control flexibility and redundancy. Their optimal distribution will also be a top research issue during this decade. Superconducting motors will become capable of producing prime movers having 10 times the power density and virtually no heat loss. This step would have the same impact on robotics as the transistor had on electronics. Every tool of interest such as adaptive control, model referencing, disturbance rejection, and so on, would take on a much higher level of relevance. This class of prime mover will become available in the second decade.

Manipulator Systems

It is increasingly possible to create several layers of control (0.1%, 1%, 99%) within the same mechanical system with separate task responsibilities associated with each level. The large scale would take on the global motion objectives now found in most robots (which are geometrically extremely simple). The next layer down (1%) might take care of deformations in the system due to forces in the process work function. The next layer down (0.1%) might take care of small changes due to temperature or electronic drift, and so on. This kind of layered architecture is very similar to that used to build up software systems. Hence, matching these hierarchical needs both in software and hardware is essential for future cost-effective robot systems. This layering is what is meant by making the system more responsive to sensor-based commands.

The modularity of personal computers is now an accepted and necessary reality of computer architecture. Those systems are layered with nearly standardized interfaces and control software. Such modularity in robotics has been pursued only in the most elementary sense. A true architecture, where local priorities, scaling issues, subsystem integration, and so on, are all involved, has yet to be dealt with. Such modularity and architecture is essential for the growth of the mechanical technologies, especially if their costs are to become more competitive. This class of architecture allows a continuous evaluation of the system while preventing obsolescence by making "tech mods" feasible at the modular level without disturbing the system.

Ultimately, the success of an aggressive technology for robotics will depend on our ability to design the system to meet a broad range of operational requirements in terms of an excess of 100 or more available system parameters (for a 6-DOF serial arm, there would be 18 geometric, 42 mass, 36 deformation, and 18 actuator parameters). Addressing all of these parameters simultaneously would far exceed the computational capabilities of the largest of foreseeable computers. Hence, a strategy for design must be developed to break the design process down into a series of layers upon which interactive intervention by the designer through simulation is possible. Computer system designers complain that they have an incomplete strategy for design. Considering the level of architecture, system definition, determinism, linearity, and so on, which exists for computers, it is not difficult to comprehend the much more severe task faced by the designer of robots which is a far less developed technology.

Forecast. Layered control (large, small, and very small actuators distributed throughout a general mechanical architecture) will become available in this decade. Modular robots will become widely available in the second decade. Finally, a full design capacity will not be available until the third decade.

Internal Decision Making and Control

As the mechanical architecture becomes more flexible, layered, and generic, it also becomes far less deterministic. Hence, criteria will have to be developed which will internally govern the system to meet its operational requirements. These criteria will be associated with precision, load capacity, redundancy, obstacle avoidance, internal force magnification, and so on. Easily 30 distinct criteria can be identified today. Hence, these criteria will have to be balanced (fused) in real time (in less than 30 ms). This high level of decision making will be essential in all future robotic systems. The criteria will be based on a full physical plant description (model reference). The implementation of this balanced decision-making is the purest form of feedforward control. The level of complexity implied would completely swamp any effort to achieve this level of capability by feedback only. Feedback will be used to sharpen the commands generated as a result of an incomplete system model, by an incomplete sensing system, or by an incorrect balancing of the criteria.

Most robots are now used to perform low-valued functions. These functions are primarily handling tasks and they add little direct value to the product. They are feasible in today's technology because the function contains almost no disturbance. Important functions (drilling, routing, grinding, force fit assembly, etc.) add high value to the product, but they do contain force disturbances which reduce the precision

of the robot due to large deflections. Hence, until we treat this type of function directly without expensive supporting jigs and fixtures, we can not obtain the level of flexibility in our increasingly batch mode manufacturing plants and we can not achieve the level of return on investment necessary to drive the technology forward. This is why robotics today has lost its acceptance in the broader community. The opportunity in airframe manufacture, the military repair depots, space operations, and so on, is enormous. Yet the present research priorities in the USA will hardly get us there unless we redirect ourselves to the central problem of disturbance rejection in the unit process.

Forecast. A full spectrum criteria-based decision-making technology will not become available until the second decade. The high-valued light machining robot will be available in the factory in this decade. It will be available in the remanufacturing environment in the second decade.

Mobility and Portability

For mobile robotic systems, no fixed base can be used as a coordinate reference. This introduces significant navigation and parametric location requirements. Vision-controlled automobiles, hovering aircraft, tracked vehicles, walking machines (and combinations of these) can be used for sentry duty for physical security, materials handling, runway repair, and weapons removal and demolition. Research problems include navigation and positional accuracy, stability in rough terrain, teleoperation from a stand-off position, and so on.

Forecast. Field operations in their first level of technology will be available in this decade. More generic and cost-effective systems will occur in the second decade. Space mobile roving systems with multiple arms will become effective in the second decade.

End-Effectors

End-effectors are the tools attached to the end of the manipulator to perform specialized functions such as welding, drilling, locking or unlocking bolt assemblies, and so on. Some end-effectors are multipurpose devices in the same sense that the human hand is able to hold a hammer, screwdriver, or other tool. All indications are that a new generic hand is required to reduce the number of special tools necessary to perform a range of unstructured tasks.

Forecast. A compact, computer-driven, multifingered hand will depend on compact localized prime movers and will not be fully available until the second decade.

HUMAN INTERFACE SYSTEMS

As these machines become more complex and increasingly self-contained in decision capability, the temptation is to assume that the machine can be considered as autonomous. In fact, what we can surely suggest is that human intervention will be less frequent but, when it is required, it will occur at a higher level and therefore require a higher quality of interface (visual, kinesthetic, voice, etc.) and that it will be increasingly analog because of the density of information flow that will be required. Hence, as system technology develops, there will be a greater need for man-machine interface—not less. This boundary should be moved slowly towards less frequent interaction, but it should rarely be eliminated entirely.

Teleoperation

The reality of unstructured tasks as might result in an accident, from other damage, or from human error, is that they will require human judgement. These tasks must be carefully evaluated to obtain actual operating requirements. Until this is done, the actual need for teleoperation will not become clear.

Forecast. It will require much of this decade to document accurately task specifications for robots in unstructured and hazardous tasks.

Universal Manual Controller

Past master-slave systems used manual controllers which were geometrically similar to the slave (or driven) manipulator. This meant that a compromise between the two was the result. Today, it is feasible to develop a manual controller which is completely different from the slave in size, geometry, number of DOF, control parameters, and so on. This means the slave can be better optimized to meet its functional needs while the controller can be better designed to interface with the human. On this basis, the controller becomes universal, that is, it is able to drive any slave system.

Some of the desired attributes of the manual controller are

1. lightweight,
2. compact,
3. stowable,
4. portable,
5. adaptable,
6. minimum friction (stiction),
7. minimum mass,
8. small minimum step (resolution),
9. transparency of force feedback signal.

Forecast. It is possible to develop a first generation universal force reflecting manual controller within a period of 5 years.

Operational Controller Software

To make a manual controller universal requires that real-time software be developed to transform signals from the controller into meaningful command signals to the slave robot. If more than one distinct slave is possible (say there are several stand-off manipulators) as would occur in space, then each combination would require its own on-board communications software. This software must operate in real time (10 ms). It must transform all encoder, force, current, and other signals into generic digital information about the state of the slave, the controller, or the interactive wishes of the operator and develop command signals to the active elements of both controller and the slave. Since extra DOF may occur in both systems, criteria based decision making will also be essential. Clearly, the duality of these transformations, the opportunity for human intervention at all levels, and the mass of the information flow creates a complexity exceeding that of just controlling the slave robot alone. Doing so, however, makes possible changes in scale, filtering of gross errors or jitters, reorientation, referencing, force smoothing, and so on. Should time lags exist of 0.5 to 2.0 sec., it appears possible to use smoothing, projected signals, and visual ghosting to make the duality still work. Essentially, the system is two robots communicating with each other in real time.

Initial prototype software packages do exist in a few research laboratories. A major effort would be required to develop a portable and reliable software system such that one controller could drive any number (say 10) of distinctly different slaves.

Forecast. Software for the universal manual controller is feasible but it will require most of the decade to develop a system suitable for field deployment.

ESSENTIAL RESEARCH ACTIVITY

The recommended research would concentrate on the use of the super computer to dramatically accelerate the development of a science of intelligent machines because of its superior computational capacity to treat the full parametric description of a much more general class of robot structures. For example, the massive computational resources of the supercomputer makes it possible for the researcher to think much more openly and freely of generic top down design and control strategies which should lead to a maximum level of productivity of new ideas and technology evaluated by complete simulations. This increased computational capacity will mean that the following can be addressed:

1. **Robot architecture.** Future robots will be composed of easily scaled structural modules (elbows, knuckles, shoulders, wrists, micro-manipulator, mixed large and small control structures, etc.) to provide finite packages of proven technology to be rapidly assembled into generic intelligent machines.
2. **Redundant structures.** *Serial machines* (snake-like systems) have excess inputs for a very high level of dexterity and obstacle avoidance capability, but require a correspondingly high level of decision making intelligence to operate in real time (for enhanced precision, load capacity, speed, etc.).
3. **Optimal design.** Initial success in the use of optimization techniques to the multi-parameter multi-criteria problem associated with robotics has led to improved distribution of actuator parameters. This computationally intensive effort must be expanded to include the full range of design parameters (link dimensions, mass distribution and deformation parameters, etc.).
4. **Graphical simulation.** In order to design or operate complex robotic structures, their full operational characteristics must be on display with great fidelity to the designer as well as to the machine operator. Training functions (similar to the Link aviation trainer) will become increasingly important for surgeons (micro-surgery), nuclear reactor maintenance, space station operations, etc.
5. **Operational software.** Symbolic programming can now be applied to the complex analytical formulations required to completely describe the dynamic state of a robot and to form the basis for a generic operational language capable of off-line programming and disturbance rejection. Proven formulations can be imbedded in dedicated processors to provide hardened, very high speed computations.
6. **Sensor fusion.** The sensor subsystem must provide data on the operation of the robot and its interaction with the environment. System sensors include force, position, velocity, acceleration, actuator currents, etc. Process sensors include range finding (to obstacles or targets), tac-

tile, proximity, force, etc. Sensor fusion deals with the reduction of all this conflicting, incomplete, fuzzy, excessive information into predictive state commands for the operation of the system.

7. **Computer architecture.** The top down approach, made feasible by the supercomputer, will make it possible to develop specialized computer hardware and software modules (arithmetics, array processors, etc.) uniquely suited to intelligent machines. In addition, a new generation of generic, modular, layered hardware controllers must be developed to match the modular and layered mechanical architecture that will be forthcoming.
8. **Adaptive control.** This represents the real time adjustment of the control parameters to best enhance the controllability of the fully nonlinear nature of robot structures. The dynamic model must include the first, second (and some times third) order geometric representations of the system in order to account for the full cross-coupling for mass, deformation, and drive system characteristics.
9. **Decision making.** As the system becomes generalized with more redundancy (extra DOF), more layers of control (for disturbance reduction), more modular (elbows, shoulders, etc.) it will become more non-deterministic. Hence, intensive integration of AI principles will be required to balance hundreds of criteria in real time (even conflicting) in order to most efficiently use excess system resources to result in the best overall performance.
10. **Machining robot.** The heart of the factory of the future will require inexpensive generic robots to perform precision light machining operations by direct computer control in order to have a maximum value-added benefit and response to the individual consumer. This requires a complete dynamic and vibration model implemented with feed-forward compensation in real time to make the system electronically rigid.
11. **Metrology of robots.** A semi-automatic means of identifying all significant parameters in an existing robot. Unfortunately, to identify 114, or more, parameters is an extremely demanding technical task. Limited parametric knowledge of the system reduces the potential for computer-based operation.
12. **Man-machine interface.** As the technology becomes more complex, a greater need (not less) will develop for a balanced control (or intervention) by man and machine. This will require a much higher level of machine intelligence (to treat multiple slaves, changes of scale, error filtering, reorientation, time lags, etc.) to obtain the full benefit of the technology for man.
13. **Multiple arm systems.** These parallel machines include dual arm robots, multi-fingered hands, walking machines, etc. frequently having an excess of 3 to 4 times the number of prime mover commands in order to achieve the desired output (usually 6 DOF spatial motion of the output link or object). This becomes the most demanding problem for internal decision making and software development facing the robotics research community.

CONCLUSION

The critical issue facing designers of advanced robot architectures is how to take advantage of advanced electronic technol-

ogy (encoders, arithmetic chips, high speed processor boards, etc.) to produce generic and more versatile mechanical robot structures at lower costs. Today, almost all robots are designed one at a time at exceptionally high cost of resources and time. Frequently, this level of investment induces the designer to be conservative leading him to use only proven technologies—hence, his system is not only costly but frequently obsolete and can not easily be redesigned when new technology becomes available. The pressing need is to achieve an architecture which can rapidly evolve in the same fashion as is now feasible for personal computers. Hence, the community must strive to create a standard of technology for robotics in the same sense that the personal computer (the IBM AT) has become a standard for PC clones. This standard not only rapidly moves the technology forward but it also creates commercial incentive to substantially reduce costs. The first level of the technology necessary for the PC is the continuously advancing computer chip. It is contended here that the equivalent level for the robot is a universal and easily scaled finite set of actuator modules which can act as the foundation to an easily scaled, assembled, multi-layered, robot system which will be achieved at dramatically lower costs and will also provide significantly improved performance without long design-to-market cycles and the implied threat of obsolescence. Using the very best design (careful balancing of parameters), materials (rare earth magnets), environment (nitrogen cooling), structural components (carbon fiber links), etc., the potential improvement factor over present industrial robot practice can be shown to be between approximately 10^4 and 10^6 . This benefit ratio not only suggests that a revolution in mechanical technologies is feasible but that it could match the excitement now associated with microelectronics.

The economic reality is that wealth generation is 1/3 of the GNP of the USA of which 2/3 is due to manufacturing. Of this 2/3, 50% or more is mechanical in nature (shoes, clothing, cameras, industrial machine tools, etc., excluding major sectors such as aircraft and vehicles), primarily in the civil sector. Yet industry invests less than 5.5% of its R&D and its technical manpower to meet this need. The federal government invests less than 0.6% (these numbers are based on 1984–86 NSF data). These major imbalances continue to weaken our civil sector and allow penetration into our home markets by other strong civil sectors such as Japan and Germany and, in the future, France and Russia.

Hence, the technical community (especially mechanical engineering) must create some new excitement not only to garner more R&D investment from the federal government and to encourage more vigorous commercialization but it must attract into the field the bright young people who wish to make our manufacturing industry competitive with the best anywhere. Overall, the goal is to break with the past in compartmentalized design of mechanical systems, to create a low cost system of the same architectural level as a personal computer, and to make robots much more responsive to the broad range of applications where they are clearly needed. **MR**

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Delbert Tesar holds the Carol Cockrell Curran Chair in Engineering at the University of Texas at Austin. He presently leads a research team of 35 graduate students in the field of robotics with emphasis on the mechanical technologies such

as dynamic modeling, adaptive control, real-time computation, man-machine interface, modular robot architecture, and actuator development. The group is pursuing applications in nuclear reactor maintenance, space operations, microsurgery, battlefield logistics, and precision light machining. D. Tesar has held numerous national panel posts dealing with robotics (NASA, NIST, AF) and was a member of the Air Force Science Advisory Board.

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**DESIGNING EQUIPMENT FOR REMOTE HANDLING:
LESSONS LEARNED FROM NUCLEAR TECHNOLOGY**

**Satellite Services System Working Group
#22
Johnson Space Center
11/28-29/89**

**Dan Kuban
Oak Ridge National Laboratory**

REMOTE HANDLING (RH) HAS MORE IMPACT ON THE FACILITY DESIGN THAN ANY OTHER SINGLE CRITERION

- o **DEVELOPMENT OF RH TECHNOLOGY**
- o **GUIDELINES FOR DESIGNING REMOTE EQUIPMENT**
- o **IMPACTS OF RH ON EQUIPMENT AND FACILITIES**
- o **RECOMMENDATIONS FOR ACHIEVING REMOTE SUCCESS**

**THE FIRST STEP IN THE DESIGN OF EQUIPMENT FOR
REMOTE HANDLING IS TO SELECT THE RH SYSTEM**

**THE CAPABILITIES AND LIMITATIONS OF THE RH SYSTEM MUST BE WELL UNDERSTOOD
BY THE EQUIPMENT DESIGNER.**

- o **FOOTPRINT AND ENVELOPE**
- o **REACH CAPABILITIES AND MOTION RANGES**
- o **LIFTING CAPACITIES**
- o **FORCE REFLECTING CHARACTERISTICS**
- o **VIEWING/LIGHTING CAPABILITIES**
- o **INTERFACES**

**FOUR TYPES OF RH SYSTEMS HAVE BEEN USED IN THE PAST
TO PERFORM REMOTE MAINTENANCE/OPERATIONS**

- o **CRANE/IMPACT WRENCH**
- o **POWER ARMS**
- o **FORCE-REFLECTING, TELEOPERATED, MANIPULATOR ARMS**
- o **AUTOMATED DEVICES, E.G., ROBOTS**

THIS PRESENTATION WILL CONCENTRATE ON THE TELEOPERATORS

CRANE/IMPACT WRENCHES WERE THE INITIAL RH SYSTEMS USED BY THE NUCLEAR INDUSTRY

- CAPABLE OF PUTTING LARGE FORCES ON EQUIPMENT ITEMS
 - NO FORCE FEEDBACK
 - EQUIPMENT DESIGNED TO WITHSTAND HIGH LOADS
- ONE DEGREE-OF-FREEDOM (UP/DOWN)
 - ACCESSIBILITY MUST BE FROM ABOVE
 - EQUIPMENT CANNOT BE STACKED VERTICALLY
 - LARGE FLOOR SPACE REQUIRED
- OPERATING EFFICIENCY IS VERY LOW
 - UP TO 100 TIMES LONGER TASK TIME THAN TELEOPERATOR

POWER ARMS OFFERED SOME IMPROVEMENT OVER CRANE/IMPACT WRENCHES

- **ADDITIONAL DEGREES-OF-FREEDOM IMPROVE OPERATOR EFFICIENCY**
 - **ORDER OF MAGNITUDE IMPROVEMENT OVER CRANE/IMPACT WRENCHES**
 - **STILL AN ORDER OF MAGNITUDE WORSE THAN TELEOPERATORS**
 - **ADDITIONAL DEXTERITY REQUIRES LESS FLOOR SPACE**
- **CAPABLE OF PUTTING LARGE, CONCENTRATED LOADS ON EQUIPMENT ITEMS**
 - **NO FORCE FEEDBACK**
 - **JOY STICK OPERATION**
 - **EQUIPMENT DESIGNED FOR HIGH LOADS**

ROBOTS HAVE LIMITED APPLICATION FOR UNSTRUCTURED REMOTE ACTIVITIES

- **NO HUMAN OPERATOR TO ACCOMMODATE UNPLANNED EVENTS**
- **RH ACTIVITIES ARE RARELY REPETITIVE**
- **A ROBOT BECOMES ANOTHER PIECE OF EQUIPMENT TO BE MAINTAINED**

FORCE-REFLECTING TELEOPERATORS OFFER A SIGNIFICANT IMPROVEMENT IN DEXTERITY AND VERSATILITY

- **EQUIPMENT DOES NOT HAVE TO BE OVER-DESIGNED TO TAKE ABUSE**
 - **FORCE REFLECTION ALLOWS OPERATOR TO FEEL FORCES**
 - **ALLOWS USE OF STANDARD OFF-THE-SHELF COMPONENTS**
- **HUMAN CAPABILITIES ARE PROJECTED INTO THE REMOTE ENVIRONMENT**
 - **UNPLANNED ACTIVITIES CAN BE PERFORMED**
 - **SIGNIFICANT IMPROVEMENT IN OPERATOR EFFICIENCY**
- **EQUIPMENT CAN BE POSITIONED EFFICIENTLY TO MINIMIZE SPACE/VOLUME**
 - **EQUIPMENT CAN BE STACKED VERTICALLY AND STILL BE ACCESSIBLE TO RH**
 - **MORE DELICATE EQUIPMENT BECOMES REMOTELY MAINTAINABLE**

**FORCE REFLECTION HAS BEEN SHOWN TO BE VERY
IMPORTANT FOR EFFECTIVE TELEOPERATIONS**

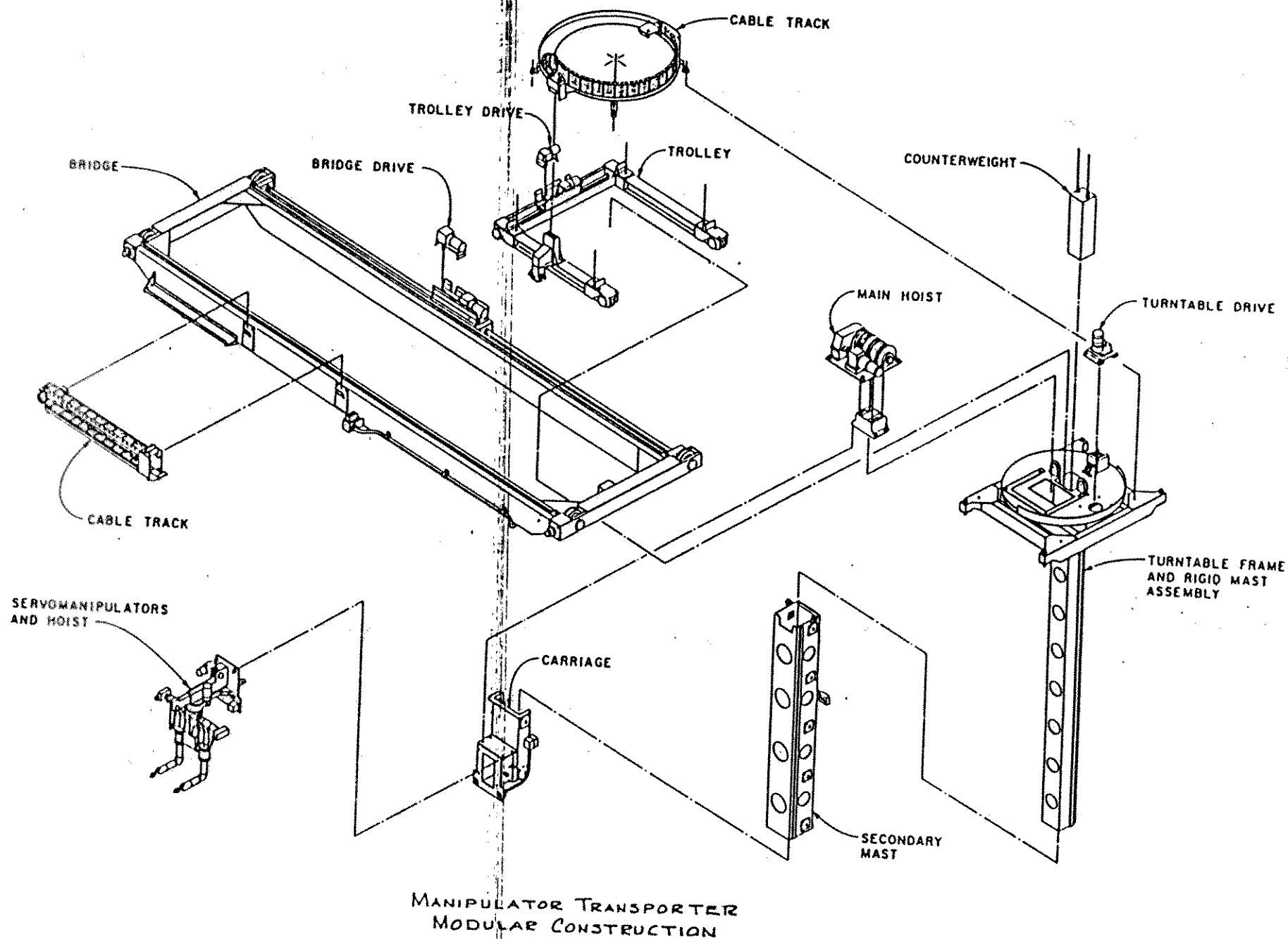
- **LOWER FORCES ON EQUIPMENT (LESS DAMAGE)**
- **LESS MISTAKES**
- **LOWER TASK TIMES**

**TRANSPORTERS AND VIEWING ARE JUST AS
IMPORTANT AS THE TELEOPERATOR ITSELF**

- **TV VIEWING ALONE DOUBLES TASK TIME**
- **SHADOWS AND LIGHTING ARE MOST IMPORTANT DEPTH CUES**
- **MORE TIME IS SPENT POSITIONING THE CAMERAS AND THE TELEOPERATOR THAN PERFORMING THE TASK**

DESIGNING FOR REMOTE MAINTENANCE

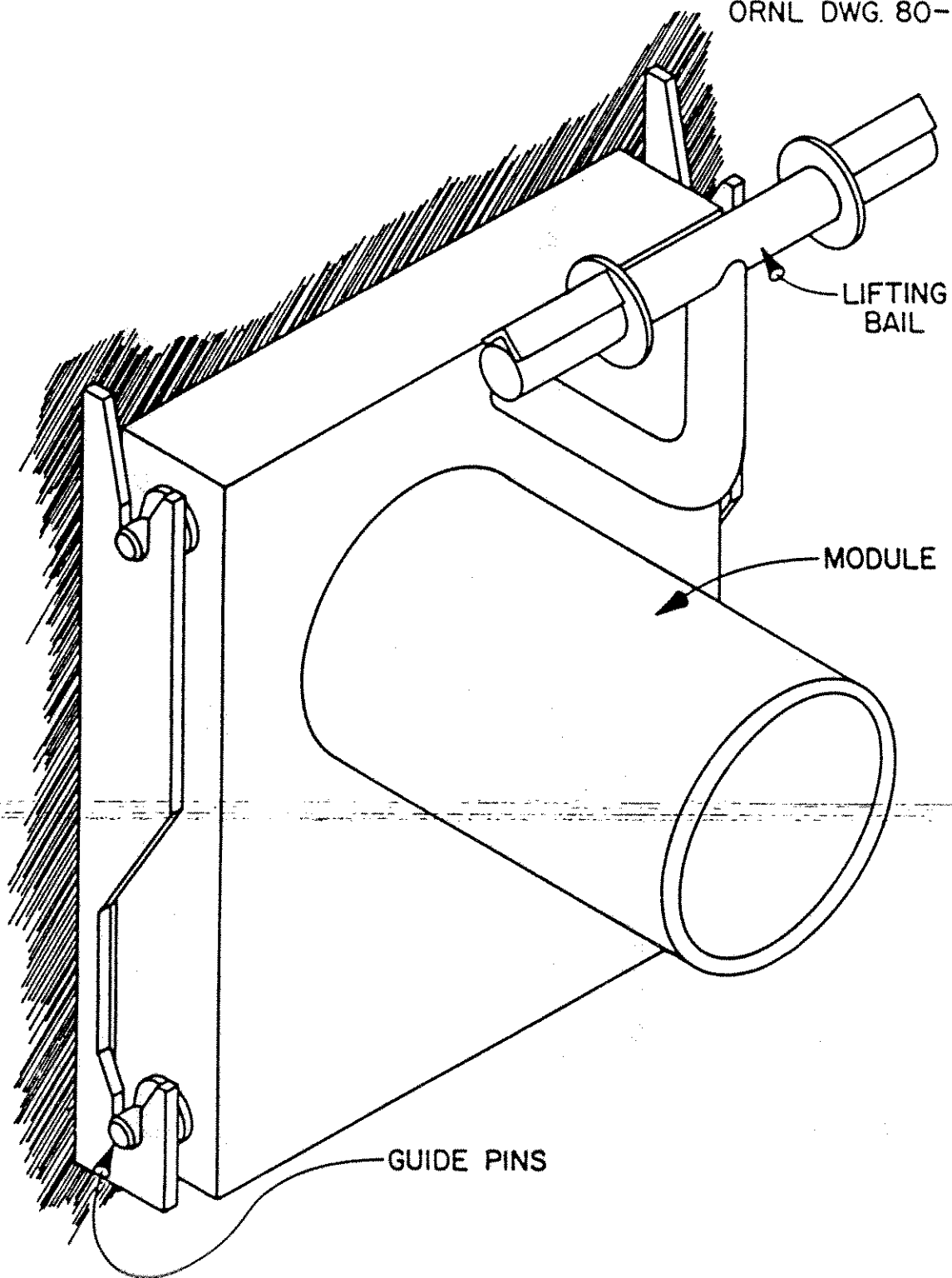
- **NO GADGETS PLEASE**
 - **DEGRADES REMOTE MAINTENANCE**
 - **INCREASES COMPLEXITY AND DECREASES RELIABILITY**
- **ACCESSIBILITY WITH TELEOPERATOR**
 - **W/O SPECIAL FIXTURES**
 - **CLEAR TV VIEWS**
 - **MINIMUM DISTURBANCE TO ASSOCIATED EQUIPMENT**
- **MODULAR COMPONENTS**
 - **SIMPLE MOTIONS OF TELEOPERATOR**
 - **LIFTING BAILS, GRIPS ON EQUIPMENT, CENTER OF GRAVITY LOCATED**
 - **BAILS WITHIN TV VIEWS**



DESIGNING FOR REMOTE MAINTENANCE (CONTINUED)

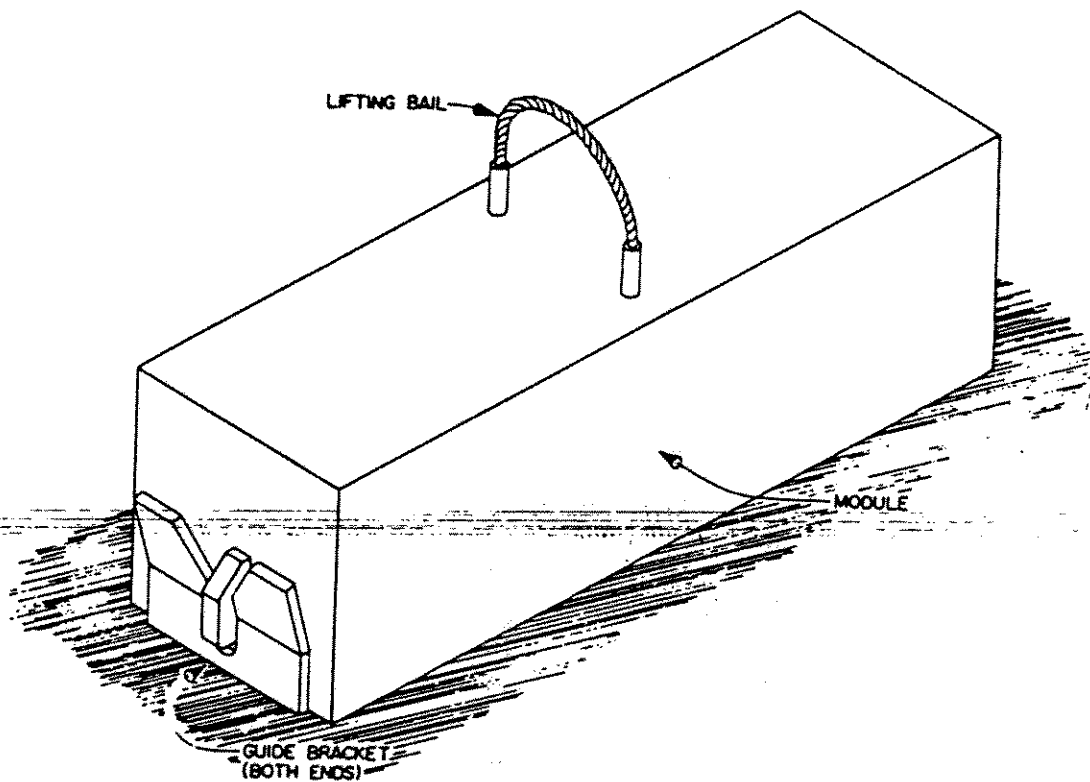
- o STORAGE SPACE
 - SPARES OR REPLACEMENTS
 - FLOOR SPACE ALWAYS PREMIUM
- o SIMPLE, SELF-ALIGNING INTERFACES
 - SEQUENTIAL, TWO STAGE ALIGNMENT: GROSS AND PRECISION
 - PRECISION ALIGNMENT: 2 MAX, SHORT TRAVEL
 - REST POINTS, STABLE MOUNT W/O BOLTS
- o NO CLOSE TOLERANCES
 - PARTS SHOULD FALL TOGETHER
 - IF PRECISION REQUIRED USE SEQUENTIAL SHORT TRAVEL

ORNL DWG. 80-6843



VERTICAL HANGER BRACKET

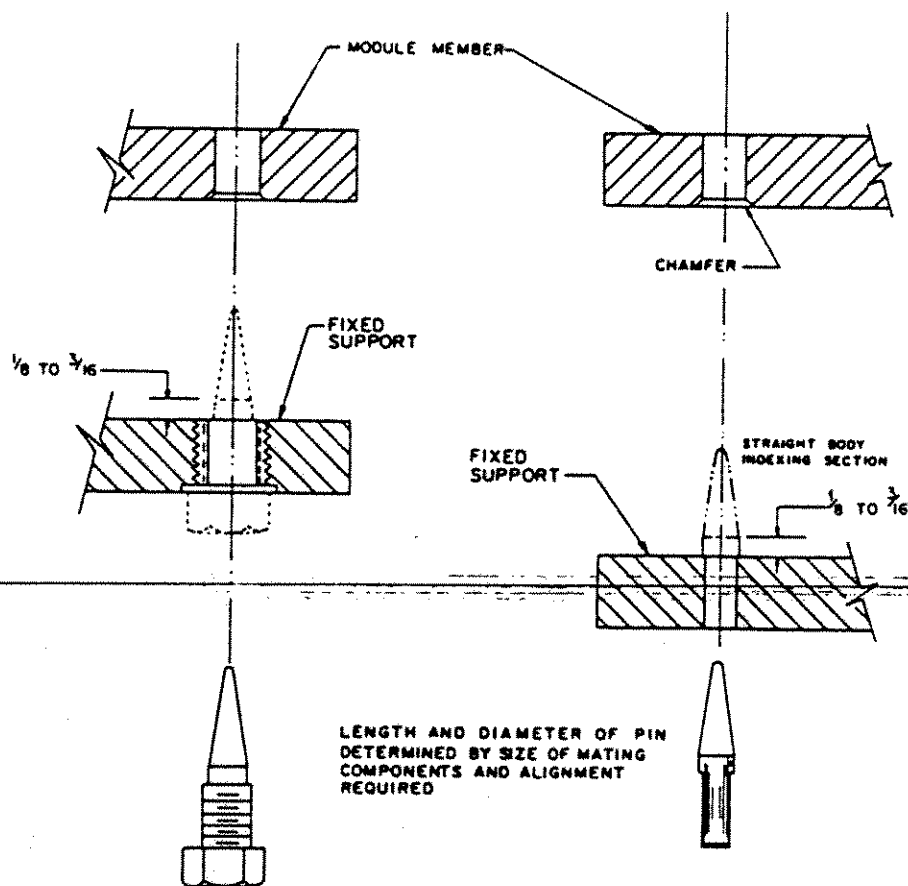
OAK RIDGE NATIONAL LABORATORY		80-6842
REMOTE HANDLING DATA SHEET		DATE MAY 1980
TITLE: VERTICAL GUIDE BRACKETS		APP:
		REF DWG. X3E-13463-6
		REV. 1



DESIGNING FOR REMOTE MAINTENANCE (CONTINUED)

- o NO LOOSE PARTS
- o MINIMIZE SPECIAL TOOLS
- o CONSIDER LIFETIME COSTS
- o STANDARDIZE FASTENERS AND CONNECTORS
 - COMMERCIAL
 - ONLY A FEW SIZES

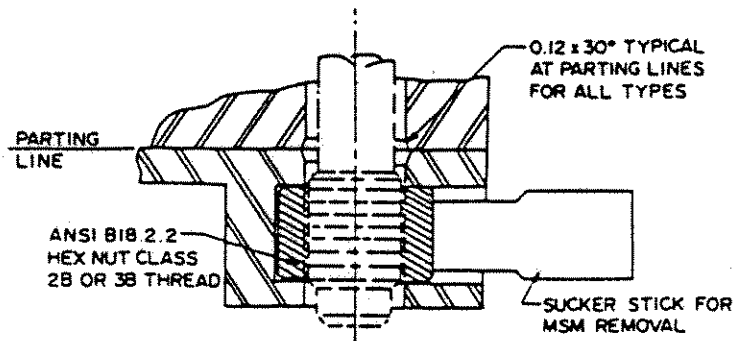
OAK RIDGE NATIONAL LABORATORY		79-6974
REMOTE HANDLING DATA SHEET		DATE MAY 1980
TITLE: GUIDE PINS		APP:
		REF DWG.
		REV. 2



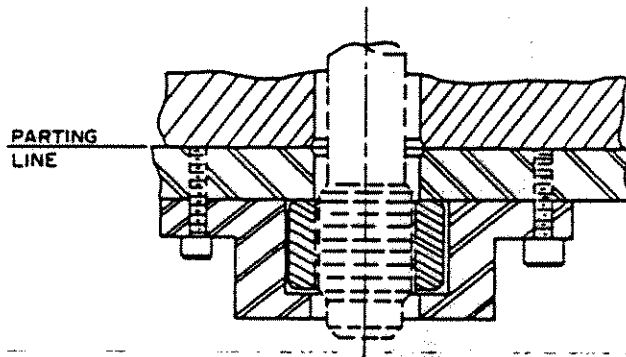
NOTE: REMOVABLE GUIDE PINS
NEED TO BE SELF-RETAINED

GOOD FASTENER DESIGN IS ESSENTIAL

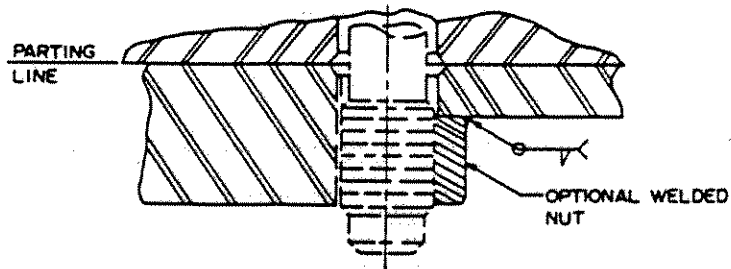
- o ALL CAPTIVE (NO LOOSE PARTS)
- o NO SLOTS, INTERNAL SOCKETS
- o NONE LESS THAN 1/4 INCH
- o COARSE THREADS
- o HARDENED MATERIAL (17-4 PH)
- o GALLING RESISTANT (NITRONICS)
- o AVOID CROSS-THREADING
 - ROOT LEAD, BLUNT START, ACME
- o FASTENERS STAY WITH MODULE
- o PERMANENT PART STRONGER
- o NO SNAP RINGS, COTTER PINS, ROLL PINS



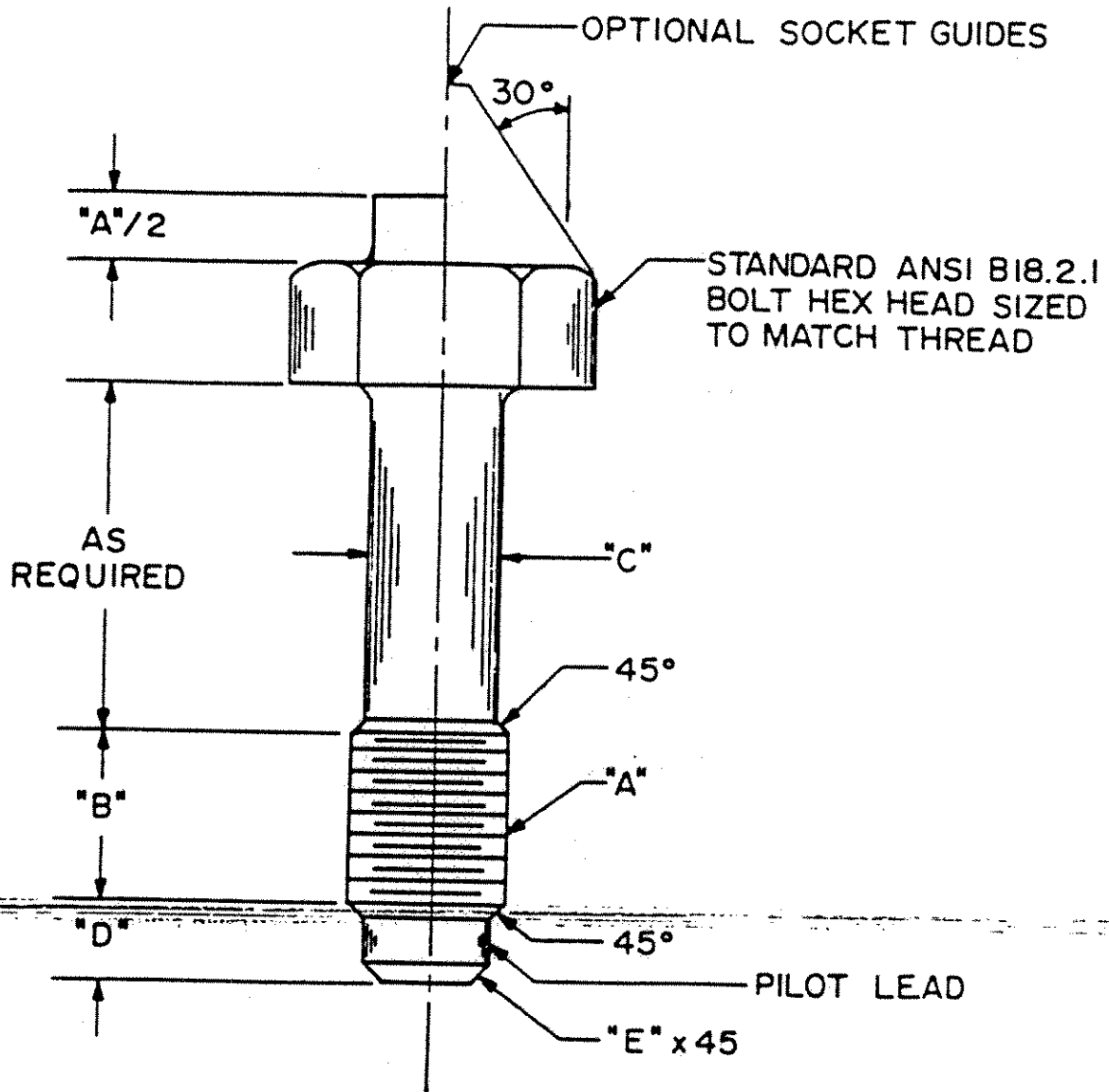
TYPE I RETAINED NUT



TYPE II-CAPTURED NUT

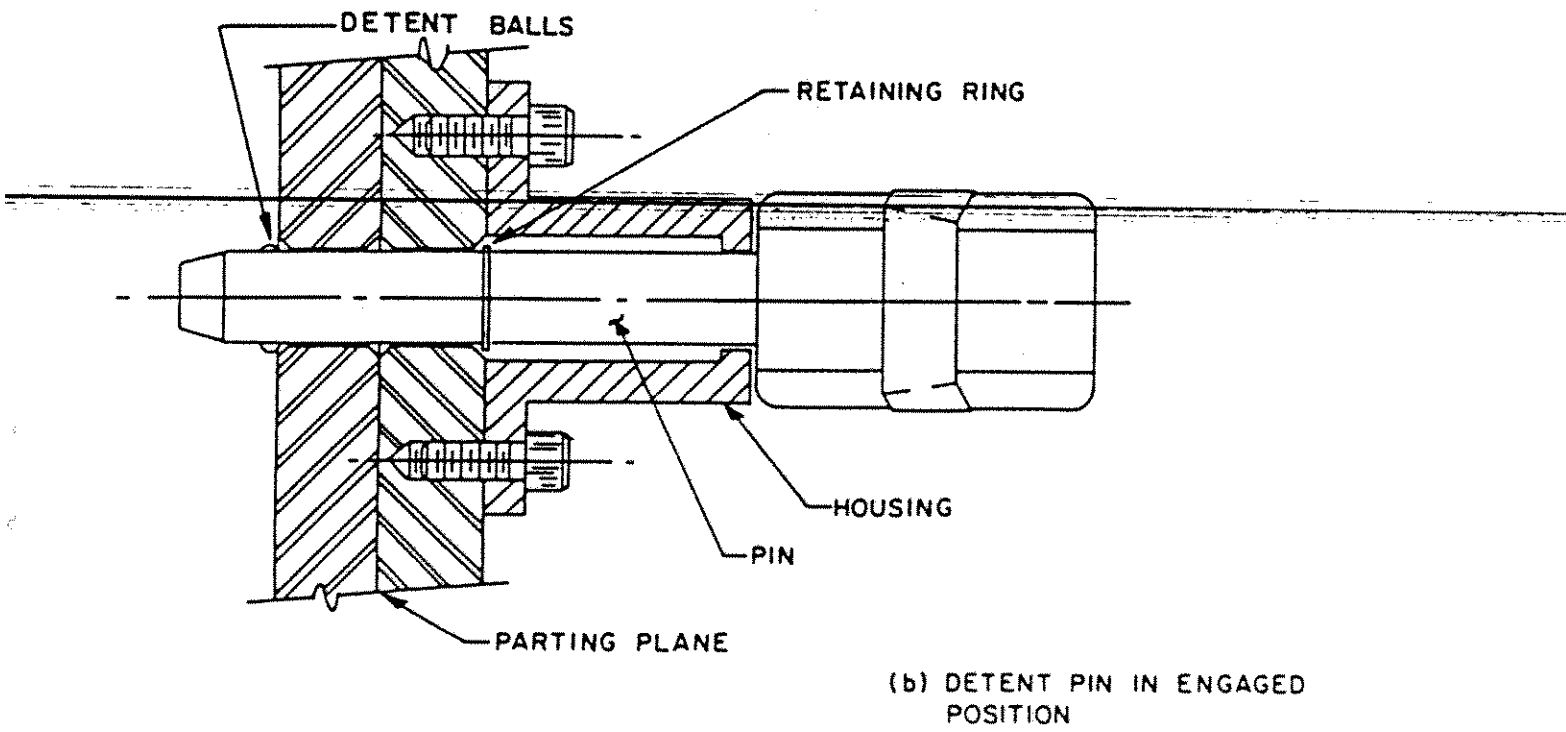
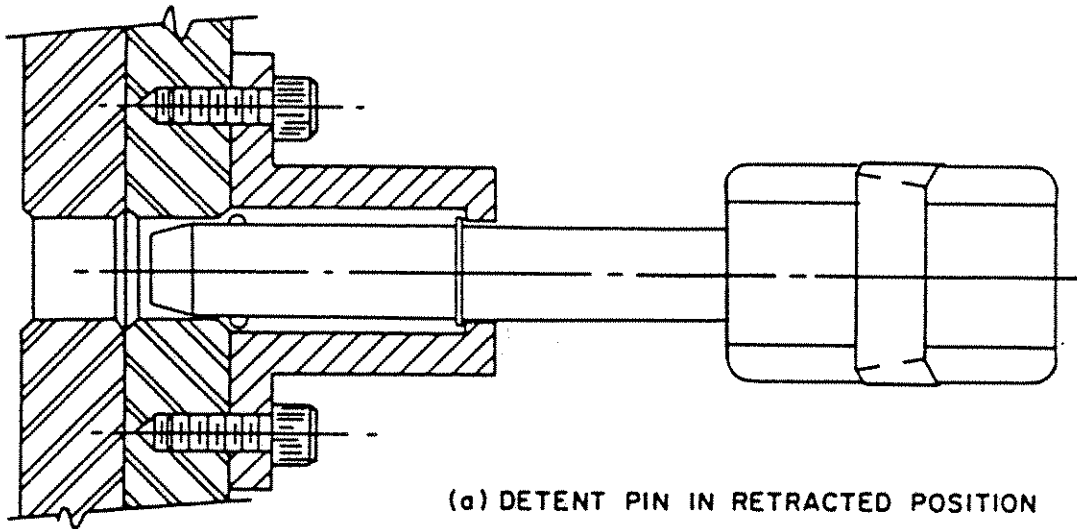


TYPE III PERMANENT THREAD



BOLT SIZE ("A")	"B"	"C"	"D"	"E"
1/2 NC 13-2A*	0.50	0.40	0.38	0.06
3/4 NC 10-2A	0.70	0.63	0.50	0.06
1 NC 8-2A	0.90	0.85	0.50	0.12
1 1/4 NC 7-2A	1.10	1.07	0.63	0.12

*A MINIMUM OF CLASS 2A THREADS ARE REQUIRED WITH
3A OPTIONAL.



**VIDEO OF TELEOPERATIONS
ON NUCLEAR HARDWARE**

**VIDEO OF TELEOPERATIONS
WITH SPACE HARDWARE**

GRAPHIC MODELING IS A VERY EFFECTIVE TOOL FOR RH DESIGN

- o **CONCEPTUAL DESIGN TOOL**
- o **WHAT-IF DESIGN ANALYSIS**
- o **ACCESS AND REACH ASSESSMENTS**
- o **INTERFERENCE CHECKS**
- o **OPERATIONAL SIMULATION**
- o **NO CRITICAL FEATURE VERIFICATION**

**VIDEO OF TELEOPERATION
USING GRAPHIC SIMULATION**

REMOTE HANDLING HAS A MAJOR IMPACT ON THE MISSION

- EQUIPMENT IS LARGER, HEAVIER, MORE EXPENSIVE
- TYPICAL TASKS TAKE 8 TIMES LONGER
- RETROFITTING IS EXPENSIVE TO IMPOSSIBLE
- HISTORICAL FAILURES FROM DEFICIENCIES
- RECOVERY FROM UNEXPECTED FAILURES THE BIGGEST PAYBACK
- TECHNOLOGY/EXPERIENCE GAP BETWEEN EQUIPMENT DESIGNERS AND RH ENGINEERS

THE 40 YEAR HISTORY OF RH OFFERS SOME ADVISE

- o **MANDATE RH REQUIREMENTS SHARE EQUAL STATUS WITH OTHER REQUIREMENTS**
- o **DESIGN FOR RH FROM DAY 1**
- o **INTERACTION WITH OFFICERS IS ESSENTIAL**
- o **GRAPHIC MODELLING FOR "WHAT-IFS"**
- o **CRITICAL FEATURES MUST BE VERIFIED ON PROTOTYPE MOCKUPS**
- o **TEACHING, CONTROLLING, REVIEWING, COORDINATING MULTIPLE INDUSTRIAL PARTICIPANTS WILL BE BIGGEST CHALLENGE**

SEVERAL KEY ACTIVITIES ARE NEEDED FOR A SUCCESSFUL REMOTE PROJECT

- o **SELECT AND ENFORCE RH PHILOSOPHY**
- o **SELECT RH SYSTEM**
- o **DEVELOP RH DESIGN GUIDE**
- o **PREPARE RH INTEGRATION PLAN**
- o **PREPARE RH MOCKUP/DEMO PLAN**

**DESIGNING REMOTELY SERVICEABLE SATELLITES IS A NEW CHALLENGE
FOR TELEOPERATORS, BUT BY RUTHLESSLY IMPLEMENTING SOME KEY
STRATEGIES, SUCCESSFUL RH CAN BE ACHIEVED.**